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Towards a sustainable biobased economy in Colombia: integrated environmental and economic analyses of land use and biomass value chains

Nidia Elizabeth Ramírez Contreras

Colophon

The research was carried out at the Center for Integrated Research on Energy, Environment and Society (IREES), which is part of the Energy and Sustainability Research Institute (ESRIG) of the University of Groningen in the Netherlands. This research was funded by the bilateral program “Towards a long-term science and innovation collaboration between Colombia and the Netherlands in Biomass Valorization” (RVOTF13COPP7B). Moreover, funding support from the Palm Oil Promotion Fund (FFP), administered by Fedepalma. The views expressed in this paper do not necessarily reflect those of Fedepalma/Cenipalma.

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PhD thesis

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the decision by the College of Deans.

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by

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Executive Summary

The transformation of the energy sector is an important prerequisite to achieve climate change mitigation. Biomass can play a significant role in the energy sector considering i) its versatile applicability for transport, electricity, and heat, ii) its contribution to the diversification of the energy matrix, and iii) the development of new markets and economic growth. Bioenergy utilization can have potential positive impacts (e.g., GHG emission reduction, job creation, rural development). However, also various sustainability concerns exist, which often relate to the production of biomass (i.e., energy crops). This includes negative impacts on ecosystems (e.g., water use, biodiversity, indirect GHG emissions), and on food security and land tenure. The key factors for sustainable production of energy crops are i) increased resource efficiency of both food and energy crop production and their supply chains, and ii) implementation of strategic land-use planning, including conservation of natural vegetation for biodiversity and carbon values, and using underutilized land for energy crop production. Agricultural intensification is deemed important to meet the various land use needs and to reduce the impacts of direct land use change (LUC) and the risk of indirect LUC, including the associated environmental and economic impacts. However, considerable research gaps remain regarding the understanding of sustainability impacts of biomass production in the context of agricultural management and how to minimize negative impacts and maximize benefits.

Colombia is recognized as a key country for the production and utilization of bioenergy in Latin America. It also has considerable potential for improving agricultural efficiency. The future of sustainable biomass supply for energy purposes in Colombia largely depends on an integrated management of the entire agricultural crop, energy crop, and cattle production sector. The Orinoquia region is a key example with a high potential land availability for energy crop production due to low yields reported in agricultural cropping and cattle production. Colombia and the Orinoquia region serve as case study regions for analyzing the impacts and prospects of biomass production and use with improved analytical methods.

This PhD thesis aims to i) evaluate the environmental and economic performance of biomass production for energy and materials in Colombia and ii) to define strategies to work towards a more sustainable production of biomass. The aims are addressed by the following research questions:

1. What are the environmental and economic impacts of different biomass production systems at national and regional level considering different management practices and land use scenarios?
2. What are the key measures to improve the environmental and economic impacts of biomass production in the future?
3. How can analytical frameworks be designed to facilitate the regional integrated assessment of land use and impacts of bioenergy scenarios and how can such frameworks strengthen governance for future sustainable biomass production?

The environmental and economic impacts of biomass production (**question 1**) are diverse and depend mainly on previous land use, current and improved agricultural management practices, and the adopted production systems. Five main environmental and economic aspects were analyzed in this thesis: i) land use and land-use changes (LUC), ii) GHG emissions, iii) biodiversity, iv) water, and

v) economic performance, which were identified as the key aspects by analyzing eleven certification systems for sustainable biomass production and bio-based products. The certification schemes analyzed can be used to reduce negative impacts of biomass production on the environment, society, and economy. All aspects here were analyzed at regional level for three different crops (oil palm, sugarcane, and acacia) and different land use scenarios for 2030, while GHG emissions and economic performance were also assessed in more detail for palm oil at national scale for the current situation and for two future scenarios. In future scenarios, improvements in the crude palm oil production chain will facilitate a 55% decrease in GHG emissions compared to the present situation. Increase in palm crop yield is one of the strategies considered to mitigate direct and indirect (I)LUC and related GHG emissions. Sustainable oil palm production could be made possible by combining increased crop yields with the use of available agricultural land that is suitable for oil palm and has low carbon stocks. Regarding the economic performance, it shows that in an optimized production chain, the capital expenditure and operational expenditure will decrease by approximately 20%. Zooming in to the case study of the Orinoquia region indicates the importance of agricultural intensification, especially in cattle production. The medium and high intensification scenarios for agriculture in this region allowed for the production of energy crops on surplus land (i.e., 0.6 and 2.4 Mha). However, if current inefficient management practices continue or if only a low intensification is achieved, 26%–93% of the existing natural vegetation areas of the Orinoquia region will be converted for agricultural production by 2030.

Analysis of the environmental and economic impacts of land use scenarios for the region showed: 1) GHG emissions of agricultural intensification (food crops and livestock) result in up to 83% emission reduction in Orinoquia's agricultural sector compared to a business-as-usual scenario. This is largely due to increasing productivity of cattle production and improvement of degraded pastures. Bioenergy, i.e., sugarcane-bioethanol, oil palm-biodiesel, and acacia-bioelectricity produced on surplus land from such agricultural intensification results in GHG emission reductions of more than 100% compared to their fossil fuel equivalent. 2) Producing bioenergy on surplus land can positively impact biodiversity avoiding the conversion of natural vegetation into agricultural lands. 3) In addition to precipitation, irrigation is needed for perennial energy crops during the dry season. However, the use of irrigation water could be reduced by up to 27%, using efficient water management strategies. Direct water intake by cattle is quite small compared to the water consumption by crops. 4) Agricultural intensification and bioenergy production resulted in increased profitability from cattle production and from bioenergy crop production. Depending on the energy crop assessed and proposed scenario, an additional 0.8 to 12.6 billion USD per year from energy crop production could be generated in the Orinoquia region.

The key measures to improve the environmental and economic impacts of biomass production in the future (**question 2**) include a combination of measures and policies on land-use planning, agricultural management improvements, and agricultural intensification. Measures to improve the palm oil production chain were assessed at the national level (yield increase, efficient use of chemical fertilizers and fossil fuels, LUC mitigation, and value-added biomass production) and measures to increase agricultural productivity (intensification) in the areas currently in use for agriculture were assessed at the regional level. In this case, measures to lead lower land use per unit of output included increase yields for food-crops, beef production, and energy crops, planning the crop location (taking into account soil quality and water availability), and ILUC mitigation. Also, implementation of good agricultural practices to lead GHG emissions reduction (efficient use of chemical fertilizer and fossil fuels) were considered. To regional level, the key measure to reduce land use and ILUC and its related emissions is to improve livestock management. Moreover, intensification may lead to the generation of surplus land that can be used to produce bioenergy with low-ILUC-risk, thereby minimizing the related impacts. Furthermore, a combination of agricultural intensification and bioenergy production on the resulting surplus land can be a cost-effective strategy because it is possible to obtain increased agricultural outputs at lower costs, and improved profitability from energy crop products. Integration of strict laws for the protection of natural resources and the use of binding certification systems is required to safeguard such desired outcomes.

The regional integrated assessment of land use and impacts of bioenergy production can be analyzed with different interlinked methods for the evaluation of combined food and bioenergy production including a comprehensive analysis of various impacts such as GHG emissions (LUC, crop, cattle, and bioenergy), water (soil-water balance, water intake), biodiversity (MSA index), and economic performance (NPV) (**question 3**). A full value-chain perspective of the Colombian oil palm sector was used to analyze GHG emissions and economic performance, and an integral methodological framework was used to investigate the effect of different land use scenarios for future combined production of food and bioenergy with respect to GHG emissions, water, biodiversity, and the economic performance of those sectors in the Orinoquia region. The methods were designed in such a way to allow for quick screening and assessment of future (and largely uncertain) developments in agricultural production for food and bioenergy and to accommodate limitations with respect to primary information and data availability at (sub)regional or national level.

As key conclusions of this thesis, it is highlighted that i) improving agricultural practices can be an effective strategy for reducing the pressure on natural land in Colombia and can allow for increasing sustainable biomass production for energy and materials; ii) better data and spatial planning is needed at a local scale to avoid the use of areas with natural vegetation that currently have a high carbon stocks and biodiversity values; iii) the integrated approach to evaluate the impacts of land use scenarios and different management options for agricultural land use and protection of natural resources can provide a comprehensive understanding of all major environmental and socio-economic impacts on regional level;; iv) a combined analysis with energy models is desirable for optimal implementation of biobased options in the energy transition; v) the application of regulatory frameworks and stringent certification schemes needs to be part of national governance for sustainable biomass production.

Samenvatting

De transformatie van de energiesector is een belangrijke voorwaarde om klimaatverandering af te remmen. Biomassa kan een belangrijke rol spelen in de energiesector gezien i) de veelzijdige toepasbaarheid ervan voor vervoer, elektriciteit en warmte, ii) de bijdrage ervan tot de diversificatie van de energiemix, en iii) de ontwikkeling van nieuwe markten en economische groei. Het gebruik van bio-energie kan positieve gevolgen hebben (bijvoorbeeld vermindering van broeikasgasemissies, creëren van werkgelegenheid en rurale ontwikkeling). Er zijn echter ook diverse duurzaamheidsrisico’s, die verband houden met de productie van biomassa (d.w.z. energiegewassen). Het gaat onder meer om negatieve effecten op ecosystemen (bv. watergebruik, biodiversiteit, indirecte broeikasgasemissies) en op voedselzekerheid en landrechten De sleutelfactoren voor een duurzame productie van energiegewassen zijn i) een efficiënter gebruik van hulpbronnen bij de productie van zowel voedsel- als energiegewassen en de productieketens daarvan, en ii) de implementatie van strategische ruimtelijke ordening, met behoud van natuurlijke vegetatie voor biodiversiteit en koolstofopslag, en het gebruik van onderbenutte grond voor de productie van energiegewassen. Landbouwintensivering wordt belangrijk geacht om aan de verschillende landgebruiksbehoeften te voldoen en om de gevolgen van directe en indirecte landgebuiksveranderingen en de daarmee gepaard gaande ecologische en economische gevolgen, te verminderen. Er zijn echter nog grote onderzoekslacunes met betrekking tot de duurzaamheidseffecten van biomassaproductie in de context van landbouwbeheer en naar de wijze waarop negatieve effecten kunnen worden geminimaliseerd en voordelen gemaximaliseerd.

Colombia wordt beschouwd als een belangrijk land voor de productie en het gebruik van bio-energie in Latijns-Amerika. Het heeft ook een aanzienlijk potentieel voor het verbeteren van de landbouwefficiëntie. De toekomst van een duurzame biomassavoorziening voor energiedoeleinden in Colombia hangt grotendeels af van een geïntegreerde aanpak de gewas, energiegewas en veeteelt sector. De Orinoquia regio is een belangrijk voorbeeld van een regio waar veel grond beschikbaar is voor de productie van energiegewassen vanwege de lage opbrengsten die worden behaald in de gewas- en veeteelt. Colombia en de Orinoquia regio dienen als casestudieregio's voor het analyseren van de effecten en projecties van de productie en het gebruik van biomassa met verbeterde methoden.

Dit proefschrift heeft als doel i) de milieu- en economische prestaties van biomassaproductie voor energie en materialen in Colombia te evalueren en ii) strategieën te definiëren om te komen tot een duurzamere productie van biomassa. De doelstellingen worden behandeld aan de hand van de volgende onderzoeksvragen:

1. Wat zijn de milieu- en economische effecten van verschillende biomassaproductiesystemen op nationaal en regionaal niveau, rekening houdend met verschillende management praktijken en landgebruikscenario's?
2. Wat zijn de belangrijkste maatregelen om de economische- en milieueffecten van de van biomassaproductie in de toekomst te verbeteren?
3. Hoe kunnen methodische kaders worden ontworpen om de geïntegreerde regionale evaluatie van landgebruik en effecten van bio-energiescenario's te vergemakkelijken en hoe

kunnen dergelijke kaders het bestuur voor toekomstige duurzame biomassaproductie versterken?

De ecologische en economische effecten van van biomassaproductie (**vraag 1**) zijn divers en hangen voornamelijk af van het vorige landgebruik, de huidige en verbeterde landbouwpraktijken, en de toegepaste productiesystemen. In deze dissertatie zijn vijf belangrijke milieu- en economische aspecten geanalyseerd: i) landgebruik en landgebruiksveranderingen, ii) broeikasgasemissies, iii) biodiversiteit, iv) water, en v) economische prestaties. Deze aspecten werden geïdentificeerd na review en analyse van elf actuele certificeringssystemen voor duurzame biomassaproductie en bio-based producten.. De geanalyseerde certificeringssystemen kunnen worden ingezet om de negatieve effecten van biomassaproductie op het milieu, de samenleving en de economie te verminderen. Alle aspecten werden hier op regionaal niveau voor drie verschillende gewassen (oliepalm, suikerriet en acacia) en verschillende landgebruikscenario's voor 2030 geanalyseerd, terwijl de broeikasgasemissies en de economische prestaties voor palmolie ook in meer detail werden geevalueerd op nationale schaal voor de huidige situatie en voor twee toekomstscenario's. In de toekomstscenario's kunnenverbeteringen in de productieketen van ruwe palmolie de broeikasgasemissies met 55% verminderen ten opzichte van de huidige situatie. Verhoging van de opbrengst van oliepalm is een van de strategieën die worden overwogen om directe en indirecte landgebruiksverandiringen en de daarmee samenhangende broeikasgasemissies te beperken. Duurzame oliepalmproductie zou mogelijk kunnen worden gemaakt door een verhoging van de gewasopbrengst te combineren met het gebruik van beschikbare landbouwgrond met een lage koolstofwaarde die geschikt is voor oliepalmproductie . Wat de economische prestaties betreft, blijkt dat in een geoptimaliseerde productieketen de kapitaaluitgaven en de operationele uitgaven met ongeveer 20% kunnen dalen. De casestudie van de Orinoquia-regio laat het belang zien van landbouwintensivering, vooral in de veeteelt. De scenario's met gemiddelde en hoge landbouwintensivering in deze regio maakten de productie van energiegewassen op overtollig land mogelijk (d.w.z. 0,6 en 2,4 Mha). Indien de huidige inefficiënte productiemethoden echter worden voortgezet of indien slechts een matige intensivering wordt bereikt, zal 26%-93% van de bestaande natuurlijke vegetatiegebieden van de Orinoquia regio tegen 2030 in gebruik zijn genomen door voedselproductie.

Uit de analyse van de milieu- en economische effecten van de landgebruikscenario's voor de regio bleek het volgende: 1) De intensivering van de landbouw (voedselgewassen en veeteelt) resulteert in 83% emissiereductie in de landbouwsector van Orinoquia in vergelijking met een business-as-usual scenario. Dit is grotendeels te danken aan de toenemende productiviteit van de veeteelt en de verbetering van gedegradeerde weidegronden. Bio-energie, d.w.z. bio-ethanol van suikerriet, biodiesel van oliepalm, en elektriciteit van acacia die wordt geproduceerd op overtollige grond als gevolg van een dergelijke intensivering van de landbouw, leidt tot meer dan 100% reductie van de broeikasgasemissies ten opzichte van de fossiele referentie. 2) De productie van bio-energie op overtollig land kan een positief effect hebben op de biodiversiteit door de omzetting van natuurlijke vegetatie in landbouwgrond te voorkomen. 3) Naast neerslag is tijdens het droge seizoen irrigatie nodig voor meerjarige energiegewassen. Het gebruik van irrigatiewater kan echter met 27% worden verminderd door gebruik te maken van efficiënte waterbeheerstrategieën. De directe wateropname door vee is vrij gering in vergelijking met het waterverbruik door gewassen. 4) De intensivering van de landbouw en de productie van bio-energie kunnen leiden tot een hogere winstgevendheid van de veeteelt en de productie van bio-energiegewassen. Afhankelijk van het energiegewas en het scenario zou de productie van energiegewassen in de Orinoquia regio 0,8 tot 12,6 miljard USD per jaar extra kunnen opleveren.

De belangrijkste maatregelen om de milieu- en economische effecten van biomassaproductie in de toekomst te verbeteren (**vraag 2**) omvatten een combinatie van maatregelen en beleid inzake ruimtelijke ordening, verbetering van het landbouwbeheer, en intensivering van de landbouw. Maatregelen ter verbetering van de palmolieproductieketen werden beoordeeld op nationaal niveau (opbrengstverhoging, efficiënt gebruik van kunstmest en fossiele brandstoffen, vermindering van de effecten van landgebruik, en productie van biomassa met toegevoegde waarde) en maatregelen ter verhoging van de landbouwproductiviteit (intensivering) in de gebieden die momenteel voor landbouw worden gebruikt, werden beoordeeld op regionaal niveau. In dit geval omvatten de maatregelen om te komen tot een lager landgebruik per eenheid output een verhoging van de opbrengst van voedselgewassen, rundvlees en energiegewassen, planning van de locatie van de gewassen (rekening houdend met de bodemkwaliteit en de beschikbaarheid van water), en vermindering van de landgebruiksveranderingingen. Ook de toepassing van efficiënte landbouwmethoden om de uitstoot van broeikasgassen te verminderen (efficiënt gebruik van kunstmest en fossiele brandstoffen) werd meegenomen. Op regionaal niveau is m het verbeteren van het veeteelt de belangrijkste maatregel om het landgebruik en indirecte landgebruiksverandeirngen en de daarmee samenhangende emissies te verminderen,. Intensivering kan leiden tot een land surplus tov de huidige situatie, dat kan worden gebruikt voor de productie van bio-energie met een laag risico op indirecte landgebruikveranderingen, waardoor de daarmee samenhangende effecten worden geminimaliseerd. Bovendien kan een combinatie van intensivering van de landbouw en bio-energieproductie op het resulterende surplus aan land een kosteneffectieve strategie zijn, omdat het mogelijk is meer landbouwopbrengsten te verkrijgen tegen lagere kosten, en een hogere winstgevendheid van de producten van energiegewassen. Integratie van strenge wetgeving voor de bescherming van natuurlijke hulpbronnen en het gebruik van bindende certificeringsystemen is vereist om dergelijke gewenste resultaten te waarborgen.

De regionale geïntegreerde beoordeling van landgebruik en de effecten van bio-energieproductie kunnen worden geanalyseerd met een samenhangende combinatie van verschillende methoden voor de evaluatie van gecombineerde voedsel- en bio-energieproductie, waaronder een uitgebreide analyse van verschillende effecten zoals broeikasgasemissies (lansgebruiksverandering, gewas, vee en bio-energie), water (bodem-waterbalans, wateropname), biodiversiteit (MSA-index), en economische prestaties (NPV) (**vraag 3**). Enerzijds omvat dit een focus op de volledige waardeketen van de Colombiaanse oliepalmsector om de broeikasgasemissies en de economische prestaties te analyseren, en anderzijds de toepassing van een integraal methodologisch kader dat het mogelijk maakt de effecten te onderzoeken van verschillende landgebruikscenario's voor de toekomstige gecombineerde productie van voedsel en bio-energie met betrekking tot broeikasgasemissies, water, biodiversiteit en de economische prestaties van die sectoren.. De methoden zijn zo ontworpen dat ze een snelle screening en beoordeling van toekomstige (en grotendeels onzekere) ontwikkelingen in de landbouwproductie voor voedsel en bio-energie mogelijk maken en dat ze rekening houden met beperkingen met betrekking tot de beschikbaarheid van primaire informatie en gegevens op (sub)regionaal of nationaal niveau.

Als belangrijkste conclusies van deze dissertatie wordt benadrukt dat i) verbetering van landbouwpraktijken een effectieve strategie kan zijn om de druk op de natuurlijke grond in Colombia te verminderen en om een toename van duurzame productie van biomassa voor energie en materialen mogelijk kan maken; ii) betere gegevens en ruimtelijke ordening op lokale schaal nodig zijn om te voorkomen dat natuurlijk gebieden gebruikt worden die een hoge koolstofvoorraad en biodiversiteitswaarde hebben; iii) de geïntegreerde aanpak om de effecten van scenario's voor landgebruik en landbouw en verschillende beheersopties voor het gebruik van landbouwgrond en de bescherming van natuurlijke hulpbronnen te evalueren, een integraal inzicht kan verschaffen in de belangrijke milieu- en sociaal-economische effecten op regionaal niveau; iv) een gecombineerde analyse met energiemodellen wenselijk is voor een optimale implementatie van biobased opties in de energietransitie; v) de toepassing van beleidskaders en stringente certificeringsregelingen deel moet uitmaken van nationale governance voor de duurzame productie van biomassa.

Chapter 1

Introduction

1.1 Sustainable biomass production for energy

The transformation of the energy sector is an important prerequisite to achieve climate change mitigation in accordance with the aims established in the Paris Agreement to reduce global greenhouse gas (GHG) emissions for the maintenance of average temperatures below 2 °C in relation to pre-industrial levels (UN, 2015) (IEA, 2015) (Schleussner et al., 2016). Biomass can play a significant role in the energy sector considering i) its versatile applicability in transport, electricity, and heat (Daioglou et al., 2019) (IEA, 2021), ii) its contribution to the diversification of the energy matrix to bring benefits in terms of energy security and resilience (IEA, 2021) (IRENA, 2021), and iii) the development of new markets and economic growth (IRENA, 2021). Bioenergy is projected to account for 12% (1827 Mtoe) of the world's total primary energy demand by 2030 (IEA, 2015). In addition to the use of biomass for bioenergy (biofuels, heat, and power), there is also a global interest in the utilization of biomass as feedstock for bio-based products, such as biochemicals and biomaterials, to reduce the use of fossil-based feedstocks in products such as fertilizers and polymers (Stichnothe et al., 2016) (Fang et al., 2019). The demand for biomaterials is expected to increase by approximately 3% per year up to 2035 (Souza et al., 2015). Thus, biomass is expected to be used for the production of food , feed, bioenergy, and bio-based products (Hess et al., 2016). This is termed the bioeconomy, which is a socioeconomic model that is aimed at the reduction of dependence on fossil resources and promotion of the production and use of biological resources and processes for the sustainable supply of goods and services in all economic sectors (Rodríguez et al., 2017) (European Commission, 2018).

The use of bioenergy is mainly driven by the necessity for reducing GHG emissions and fossil fuel consumption (IEA, 2015) (OECD-FAO, 2019). Additionally, bioenergy utilization can exert potential positive impacts on the economy, job creation, and rural livelihoods (Dale et al., 2013) (van Eijck and Faaij, 2014) (Junginger et al., 2019) (Dunmade, 2019). Despite the potential benefits of using biomass for bioenergy, biomass feedstock production is not uncontroversial (Brito-Cruz et al., 2016). This is because of sustainability concerns such as negative impacts on ecosystems, GHG emissions, biodiversity, water, soil quality, and social and socio-economic issues such as displacement of communities, land tenure conflicts, competition for arable land, increased market prices for crops, and food security (IEA Bioenergy, 2015) (Diaz-Chavez et al., 2016) (IPCC, 2020). The environmental and socio-economic impacts and concerns are often related to land use and direct or indirect land use changes caused by the production of biomass feedstock (IEA Bioenergy, 2014) (IPCC, 2020). Therefore, it is important to understand the preconditions, management strategies, and governance options that can ensure that land use change with respect to bioenergy utilization is minimized to enable mitigation of climate change in a sustainable manner.

The key factors for the sustainable production of biomass/energy crops are: i) increase in resource efficiency of both food and energy crop production and their supply chains, which implies increase in crop yields and reduction in losses and waste generation in the supply chain; and ii) implementation of strategic land use planning, including conservation of natural vegetation for biodiversity and carbon values and using underutilized land, such as degraded, marginal, or abandoned agricultural land for energy crop production (Wicke et al., 2012) (IEA Bioenergy, 2014) (Brinkman et al., 2017) (Kerdan et al., 2019). This can help reduce the pressure on land and mitigate the negative impacts of land use change (LUC) resulting from biomass production (IEA Bioenergy, 2014) (IPCC, 2020). Bioenergy is reportedly more beneficial when biomass production is integrated into existing land uses (i.e., land already in use for food crops or livestock), and may lead to a reduction in GHG emissions, improvement of degraded soils, reduction in biodiversity loss, and retainment of water (Van Der Hilst et al., 2012) (Creutzig et al., 2015) (Brinkman et al., 2018) (Younis et al., 2021). Several strategies can support the process of integrating biomass production into existing agricultural practices (Diaz-Chavez et al., 2016), most notably by increasing yields per hectare and by enabling less occupation of land for use in other agricultural activities (Creutzig et al., 2015). For example, production of energy crops on surplus land obtained through agricultural intensification reduces the risk of direct LUC and indirect land use change (ILUC) and related GHG emissions (de Souza et al., 2019) (Gerssen-Gondelach et al., 2017) (Brinkman et al., 2018).

Achieving sustainable feedstock production for bioenergy and biomaterials relies on the engagement of concerted efforts by all stakeholders, institutions, and governments to promote sustainable management strategies and good governance (Hess et al., 2016) (Diaz-Chavez et al., 2016). Additionally, certification schemes with environmental and socioeconomic criteria can help establish whether a certain production strategy leads to the exertion of any negative impact (van Dam et al., 2010) (Diaz-Chavez et al., 2016). Certification schemes can either be voluntary (e.g., Better biomass, ISO 13065, and ISCC) or mandatory (European Parliament, 2009). An example of a mandatory certification scheme is the European Union's Renewable Energy Directive (RED). This directive has been updated on several occasions, and it has been further refined in the recast of the directive in 2018 (REDII) (European Parliament, 2018). The use of certification schemes can contribute to sustainable production of biomass and bio-based products through the reduction and prevention of impacts related to (I)LUC, biodiversity, GHG emissions, water, competition between uses of land, along with other important socioeconomic conditions (Creutzig et al., 2015) (Souza et al., 2015). Considering the aforementioned, from now on the focus of this study aims on the production and use of biomass for energy purposes (bioenergy) as this currently the most used application.

1.2 Bioenergy in Latin America and Colombia

Presently, in Latin America, the production and use of bioenergy is promoted as a strategy to address climate change (Rodríguez et al., 2017) (UNFCCC, 2020). Countries in Latin America demonstrate considerable experience with bioenergy production [36], and several countries in the region are involved in the production of bioenergy. Table 1 shows an overview of the current production statistics of biofuels and bioelectricity for a few major producers in Latin America. For example, Brazil is the largest producer of sugarcane bioethanol, Argentina is the largest producer of soybean biodiesel, and Colombia is the largest producer of oil palm biodiesel (Brito-Cruz et al., 2016). National policies or renewable energy targets that are implemented in these countries with regard to the production of bioenergy (Table 1) are diverse and refer to both the promotion of production and the development of the market, generally by means of adopting several blending mandates. Most countries have legislation regarding biofuels, except Costa Rica, Cuba, Venezuela, and Ecuador (Rodríguez et al., 2017). Brazil is one of the countries in Latin America that reports a large fleet of flex-fuel vehicles. Thus far, according to the legislation, vehicles run using either with a mixture of gasoline and bioethanol (E27) or using 100% bioethanol (E100), while for biodiesel, there is a blending mandate of 10% (B10) (OECD-FAO, 2019). Brazil is also one of the main countries involved in the use of biomass (sugarcane bagasse) to produce bioelectricity, which represents approximately 8% of the country's total electricity production (Brito-Cruz et al., 2016).

Table 1. Bioenergy-producing countries in Latin America, based on recent reports.

Country	Type of bioenergy [a]			Bioenergy production [b]	Policies/Renewable energy targets [c]
	E	B	BE		
Argentina	x	x	x	National blend: E10, B10 Around 3% of the national electricity come from biomass.	Law Act 26093 to produce and use biofuels (soybean and sugarcane). Law Act 26190 and Law Act 27191 for the use of renewable energy sources to

					generate electric power (e.g., biomass from forest, agricultural and livestock residues, and biogas).
Brazil	x	x	x	National blend: E27, E100, B10. 8% of national electricity comes from biomass	Law 9478/1997 established the guidelines of the national energy policy that includes alternative sources of energy (e.g., firewood, cane bagasse and cellulosic lye). Law 11097/2005 provides the introduction of biodiesel in the energy matrix (e.g., castor bean, rapeseed, sesame). Renewable energies participate with more than 45% of the total national energy. Since the 1930s, the use of sugarcane bioethanol as fuel in vehicles began.
Colombia	x	x	x	About 600 million liters of biodiesel (B10) and 400 million liters of bioethanol (E10) were produced in 2019. Also, 2% of the national electricity come from biomass (sugarcane bagasse)	Law 697/2001 defined the use of non-conventional renewable energy sources (NCRES). Law 1715/2014 established the legal framework to implement NCRES into the national electricity grid which also include promotion mechanisms and incentives for producers.
Chile	x	x	x	National blend: E5, B2 Bioelectricity 2%	The renewable energy target is 20% electricity generation by 2025
Guatemala	x		x	25% of national electricity production comes from biomass. Ethanol blending is E10	A law is being proposed to regulate the use of fuel alcohol in vehicles.
Mexico	x			E2	The Bioenergy Law established the general aim of reducing fossil fuel dependency, reducing GHG emissions, and boosting sustainable development in the countryside, but there is no specific biofuels promotion program.
Nicaragua			x	12% of national production	There is no specific biofuels promotion program
Paraguay	x			Ethanol blending is E18	Implemented official bioenergy programs to decrease fossil energy dependence. Law 5444/2015 encouragement of fuel alcohol consumption
Perú	x			Ethanol blending is E7.8	Implemented official bioenergy programs to decrease fossil energy dependence
Salvador			x	19% of national production is bioelectricity	National Energy Policy 2010-2024 for the expansion of energy capacity and coverage, through efficiency, optimization, and savings factors. By 2026 biomass electricity target is 45 MW.
Uruguay			x	41% of the total electricity is generated with biomass	Energy Policy 2005-2030 to diversify the country's energy matrix

[a] Type of energy correspond to E = bioethanol; B= biodiesel; and BE = bioelectricity. For bioethanol and biodiesel, there is a mandatory national blending requirement that is described using the initial letter of the biofuel and a number representing the percent blending. For example, 10% bioethanol blend in gasoline is represented as E10.

[b] Bioenergy production information from (Brito-Cruz et al., 2016) (Gómez et al., 2018) (OECD-FAO, 2019) (Uruguay XXI, 2020) (Gobierno de Colombia, 2020a)

[c] It corresponds to the latest reported policy targets (FAO, 2013) (UPME and BID, 2015) (IRENA, 2015) (Brito-Cruz et al., 2016) (CEPAL, 2017) (Eras et al., 2019) (UPME, 2019) (OECD-FAO, 2019) (IRENA, 2020)

In terms of bioenergy potential, Latin America demonstrates significant potential for the production of bioenergy (bioethanol, biodiesel, and bioelectricity) (IRENA, 2015) (Brito-Cruz et al., 2016). The region shows expansion potential for its agricultural area, an advantage which can be used to increase biomass production (Rodríguez et al., 2017). Furthermore, the region possesses the option of improving the yields of land that is currently used for extensive grazing to generate surplus land that could be available for increased biomass production (Souza et al., 2015). This can be biomass in terms of first-generation energy crops (e.g., soybeans, corn, oil palm, sugarcane), as well as non-food energy crops (e.g., miscanthus, switchgrass, jatropha), forest crops, and algae (Rodríguez et al., 2017) (OECD-FAO, 2019). According to projections for the year 2050 by Daioglou et al. (2019), it is possible to have high availability of abandoned agricultural or other natural lands for the future production of energy crops in Latin America depending largely on population growth, economic growth, food demand, and technological development (i.e. yields). The potential applicability of new non-food crop options and the use of agricultural residues for the production of bioenergy also depends on the climatic conditions of each area, land availability, good management practices, and the support extended by national and international legislation and policy programs (Plath et al., 2016) (Garcia-nunez et al., 2016) (Younis et al., 2021).

Bioenergy potential expected for Latin America in the year 2050 shows variation in data with respect to the modeled studies, depending on land availability and estimated crop yields. Depending on the scenarios proposed by the authors, the potential production of bioenergy in Latin America in 2050 is estimated to be 47-110 EJ/yr for sustainable energy crop production in unused grasslands (Searle and Malins, 2015). This potential may increase to 60–120 EJ/yr if forestry, crop residues, and waste are combined (Searle and Malins, 2015). However, more recent studies have estimated a markedly lower production potential for Latin America (ranging from 20 to 25 EJ/yr) in cases of technological advancement and increase in agricultural yield on abandoned agricultural or other natural lands and primary biomass production from residues (SSP1 scenario) (Daioglou et al., 2019).

Key Latin American countries in the bioenergy potential projections are Brazil, Bolivia, Paraguay, Argentina, Colombia, and Venezuela (Brito-Cruz et al., 2016) (OECD-FAO, 2019). Colombia is recognized as a key country for the production and utilization of bioenergy (Brito-Cruz et al., 2016). In recent decades, Colombia has demonstrated experience in the production and use of biofuels and, more recently, in bioelectricity production and use (MADR, 2016a). However, the contribution of bioenergy to the national energy sector has been relatively low, making up less than 50 PJ/year (12%) of the more than 400 PJ/year in the road transport sector and close to 200 PJ/year (2%) in the electricity sector (Asocaña, 2016) (UPME, 2016a).

To stimulate the increased use of (sustainable) biomass for energy, Colombia has worked on the development of bioeconomy concept to reduce dependence on fossil resources and promote a sustainable supply of bioenergy and biomaterials (Henry et al., 2017). Through this approach, Colombia designed the "Strategy 2050", which plans for Colombia to emerge as a climate-resilient country with a carbon-neutral economy that promotes competitiveness, social inclusion, food security, strengthened governance, and a long-term sustainable economy by the year 2050 (Gobierno de Colombia, 2021). Moreover, the Colombian government defined the national policy strategy for the development of the country's bioeconomy. This strategy assumes that a sustainable bioeconomy requires sustainability of the country's biological resources, in addition to the sustainability of production, consumption, and the reuse of materials (circular economy) (Gobierno de Colombia, 2020a).

Colombia is estimated to have a biomass potential of over 43 million tons per year (600-780 PJ) based on the use of agricultural and forestry residues (Gobierno de Colombia, 2020a). In addition, the country exhibits considerable potential for energy crops production (MADR, 2016a) (DNP, 2018a). The projections of the theoretical total biomass potential (residues and energy crops) in Colombia vary according to the scenarios proposed in several studies. According to the findings reported by Gonzalez-Salazar (2016), the bioenergy potential range of 210–900 PJ includes biomass generated from agricultural and forestry residues, animal manure, and urban waste. However, upon considering different factors that may constrain the availability of biomass for energy purposes (e.g., competing uses, ecological and technical constraints), the technical potential was estimated to be 36–420 PJ (Gonzalez-Salazar, 2016). Considering the projections of energy crop, the theoretical potential may range between 1300 and 1400 PJ/yr by the year 2030 (Gonzalez-Salazar, 2016). A recent study published by Younis et al. (2021) reported that by the year 2050, Colombia could demonstrate an energy potential ranging between 1200 and 2200 PJ/yr from perennial energy crops planted on 14 Mha of surplus land obtained through the sustainable intensification of agricultural land. The study also reported that potential regional supply centers for Colombia could be identified in Orinoquia region (> 400 PJ woody biomass/oil palm), Andean region (> 100–200 PJ of sugarcane/oil palm/ woody biomass), and Caribbean region (> 100–200 PJ woody biomass/sugarcane/oil palm) for energy crops and the Pacific region for forestry and agricultural residues (> 100 PJ residues).

The Orinoquia region is deemed a crucial area for the development of bioenergy in Colombia (CIAT & CORMACARENA, 2017). This region could potentially supply energy generated from sugarcane, oil palm, and eucalyptus cultivation because this region demonstrates the highest potential supply of land for energy crops in Colombia owing to the existence of surplus land from agricultural intensification (CIAT and CRECE, 2018) (Younis et al., 2021). The region has substantial tracts of extensive grazing lands that can be managed more efficiently through sustainable intensification, and this could also contribute to the reduction of LUC-related emissions (Lerner et al., 2017) (Fedegan, 2018).

1.3 Research gaps

Overall, there is an increasing need to formulate different land use strategies that allow simultaneously meeting the expected rising demand for food, feed, fiber; sustainably producing biomass for energy and material applications; and conserving nature (IEA Bioenergy, 2014) (Junginger et al., 2019) (Prüssmann et al., 2020). In view of these different demands, it is important to consider the following for sustainable production of bioenergy in Colombia: 1) increase the national energy basket ; 2) net environmental contribution in terms of reducing GHG emissions to comply with the country's environmental commitments of emissions and to reduce the net impact on water and biodiversity resources; 3) contribution to job creation, particularly in rural areas; and 4) adoption of scientific and technological developments that contribute to reducing impacts and producing bioenergy efficiently (UPME, 2016b).

To fulfill the expectations of sustainable land use, Colombia categorized land into zones according to its availability and suitability for different agricultural activities (agricultural, forestry, pastureland) (MADR, 2018). However, in order to minimize the negative impacts of biomass production for energy purposes, additional concerns must be addressed to establish the potential for biomass production and avoid the occurrence of negative environmental and economic impacts. For example, in Colombia, the current use of agricultural and cattle land demonstrates low productivity (DNP, 2018b). Additionally, although a zone of natural vegetation was demarcated for agricultural expansion, those areas of natural vegetation should be evaluated and potentially excluded at the local level to minimize the impacts that come from the transformation of natural areas into agricultural areas. Limits should also be established on the conversion and use of land with natural vegetation and high carbon content, into agricultural lands (Prüssmann et al., 2020).

In addition, to support minimizing the potential impacts of production and use of biomass as a feedstock, a detailed evaluation of biomass sustainability in terms of environmental and socioeconomic concerns is needed (Souza et al., 2015) (Diaz-Chavez et al., 2016). Although, several studies have been conducted to analyze and assess the sustainability impacts of biomass supply chains and to propose mitigation measures (Batidzirai et al., 2012) (Castanheira et al., 2014) (Rincón et al., 2014) (Creutzig et al., 2015) (Brinkman et al., 2017) (Batidzirai et al., 2016) (Mekonnen et al., 2018) (Wu et al., 2018) (Palandri et al., 2019) (Tapasco et al., 2019), more information is required to assess both the energy crop production and its related impacts. For example, in Colombia, the following three agricultural sectors have gained prominence with respect to the production of biomass for energy purposes: sugarcane, oil palm, and forestry. Among these, the oil palm sector has received the most considerable attention during evaluation of the impact of its production on the soil and biodiversity of the country (Castiblanco et al., 2013) (Fedepalma, 2013).

Several studies have focused on the impact of LUC driven by oil palm crops in Colombia (Garcia-Ulloa et al., 2012) (Gauch, 2013) (Castiblanco et al., 2013) (Garcia-Nunez et al., 2016) (Vijay et al., 2016), and a few such studies have attempted to identify the GHG emissions associated with palm oil production (Henson et al., 2012) (Rivera-Méndez et al., 2017). Such studies are based on a variety of assumptions, system boundaries, and functional units to calculate and report the emissions for a limited number of mills or plantations. However, they do not involve the entire production chain of the country. At the moment evaluations are missing of the environmental impacts, such as GHG emissions, associated with current oil palm production chain and its bio-based products in Colombia and of strategies to ascertain the future of the sector. A key limitation for such evaluations has been the lack of primary data that comprehensively represents the whole oil palm sector in Colombia. However, the collection of data presents an immense challenge and, thus far, that type of data are not available.

More intensive land use may also help minimize sustainability concerns of increased biomass production or even generate benefits, such as for example for the regional economy (Brinkman et al., 2015) (Gerssen-Gondelach et al., 2017) (de Souza et al., 2019) (Younis et al., 2021). Agricultural intensification is deemed important to meet the various land use needs and to reduce the impacts of direct LUC and risk of indirect LUC, including the associated environmental and economic impacts (Dauber et al., 2012) (Jimenez and Faaij, 2012) (de Souza et al., 2019) (Gerssen-Gondelach et al., 2017) (Brinkman et al., 2018). Consequently, in Colombia, the future of sustainable biomass supply for energy purposes largely depends on an integrated management of the entire agricultural crop, energy crop and cattle production sector. However, much remains unknown about the sustainability impacts of increased biomass demand in specific regions in the country. Particularly the Orinoquia region is expected to be the center of agricultural development. Considering the low yield reported in agricultural crop and cattle production in the Orinoquia region, it is necessary to propose management alternatives to increase the efficiency of land use. Since a substantial part of this region comprises low-yielding extensive cattle production areas (Fedegan, 2018), the intensification of this sector may lead to lower land requirements (Fedegan, 2018). Several studies on LUC documented in the Orinoquia region have reported changes in carbon stocks occurring due to land conversion (Castanheira et al., 2014) (Lerner et al., 2017) (Silva-Parra, 2018). Moreover, studies have reported GHG emissions associated with agricultural production (Castanheira et al., 2014) (Peñuela et al., 2019). A few studies have also focused on the impacts of land use on biodiversity loss, water scarcity, and economic issues (Alvarez et al., 2006) (WWF-Colombia, 2012) (Gilroy et al., 2015) (Prescott et al., 2016) (López-Ricaurte et al., 2017) (WWF-Colombia, 2017) (DNP, 2018a) (Ocampo-Peñuela et al., 2018) (IDEAM, 2019) (Meijaard et al., 2020). Although such types of analyses are key to understanding the features of the Orinoquia region, there is a lack of knowledge on the bioenergy industry's dynamic interactions with food production (crops and beef) in the region. An integrated assessment of developments in the agricultural sector for food production, biomass production for energy and nature conservation is needed. Such an integrated impact analysis is important to understand the multiple impacts of agricultural production, including changes in e.g., the level of intensification, and increased bioenergy crop production. Important to understand here are potential trade-offs across impact categories and identification of optimal land use and management strategies (Creutzig et al., 2015).

Then, it is necessary to assess the LUC that results from the combined impact of increasing agricultural yields of food crops and beef production and bioenergy production on surplus land generated through intensification. Furthermore, it is also important to evaluate the impact of such changes on various environmental and socio-economic conditions in regions like Orinoquia. Important aspects are GHG emissions, biodiversity, water, and economics. Efforts for integrated analysis of the impacts of bioenergy have been made and reported by different authors (Howells et al., 2013) (Thrän et al., 2016) (Wu et al., 2018) (Vera et al., 2020). However, most studies have focused only on the prevention of ILUC and its related GHG emissions (Brinkman et al., 2018) (Castanheira et al., 2015) (de Souza et al., 2019) (Gerssen-Gondelach et al., 2017) (Kadiyala et al., 2016). Some studies have focused on the analysis of bioenergy and its socioeconomic impacts (Walter et al., 2011; Wang et al., 2014). A few studies have also addressed the impacts of bioenergy production on biodiversity and water (Mekonnen et al., 2018; Rincón et al., 2014). However, analyses that are performed to simultaneously address multiple environmental impacts and economic performance are scarce in general, and are lacking for Colombia or its relevant regions

Among the various strategies considered for more sustainable biomass production, the role of certification schemes for addressing sustainability concerns and the role of integrated assessments for strengthening governance (Diaz-Chavez et al., 2016) have been identified as particularly relevant in the case of Colombia. Several organizations and governments have reported the development of certification systems to set standards of quality in biomass/bioenergy production systems (Stupak et al., 2012) (van Eijck et al., 2014). Many biomass and bioenergy sustainability frameworks and certification systems have been developed globally, but only a few certification schemes are being applied voluntarily in Colombia (Franke et al., 2013). Although Colombia aims for sustainable biomass production, a route for the implementation of specific criteria and indicators for sustainable use of biomass has not been defined. Therefore, an analysis of the key criteria and indicators that imply the production of biomass and its value chain, together with its application, is needed and can contribute to sustainable biomass production (CREG, 2018).

In Colombia, the economic and environmental conditions for developing a sustainable bioeconomy sector are mostly positive. However, the complexity of issues such as biodiversity, water, and land use warrant integrated assessments that will help strengthen and validate the protection of natural resources and the sustainable production of bio-based products. In addition, these integrated approaches need to be able to quantify the potential for improvement in different farming systems and associated environmental and socio-economic impacts. Given the comprehensive overviews that such methods aim to give, they need to be practical and manageable. Such methods or tools also need to allow for efficient screening and make use of the sometimes-limited level of detail of available data. In the literature, there are already attempts at such an integrated analysis concerning impacts of bioenergy (Howells et al., 2013) (Thrän et al., 2016) (Vera et al., 2020) (Wu et al., 2018), but most of them have focused only on prevention of (I)LUC and its related GHG emissions (Brinkman et al., 2018) (Castanheira et al., 2015) (de Souza et al., 2019) (Gerssen-Gondelach et al., 2017) (Kadiyala et al., 2016) (Ramirez-Contreras et al., 2021). Some studies have also focused on the analysis of bioenergy and its socio-economic impacts (Walter et al., 2011) (Wang et al., 2014) and a few studies addressed the impacts of bioenergy production on biodiversity and water (Mekonnen et al., 2018) (Rincón et al., 2014). Analyses that address multiple environmental impacts and the economic performance at the same time are, however, scarce in Colombia. Moreover, for the Orinoquia region of Colombia, such an integral impact analysis is important to understand the multiple impacts that agricultural intensification and increased bioenergy crop production can have, including potential trade-offs across impact categories, and to identify optimal land use and management strategies (Creutzig et al., 2015).

Taken together, important research gaps exist regarding the understanding of the sustainability impacts of biomass production in the context of agricultural developments and demands for nature conservation, and measures to minimize burdens and maximize benefits. The cumulative findings obtained from these analyses will aid the formulation of better sustainable policies and certification systems that will strengthen the implementation of sustainable biomass production for energy and material purposes in Colombia. Corresponding methods and detailed data collection are still underdeveloped and require more attention.

1.4 Thesis objective and research questions

This PhD thesis aims to i) evaluate the environmental and economic performance of biomass production for energy and materials in Colombia and ii) to define strategies to work towards a more sustainable production of biomass.

The aims are addressed by the following research questions:

4. What are the environmental and economic impacts of different biomass production systems at national and regional level considering different management practices and land use scenarios?
5. What are the key measures to improve the environmental and economic impacts of biomass production in the future?
6. How can analytical frameworks be designed to facilitate the regional integrated assessment of land use and impacts of bioenergy scenarios and how can such frameworks strengthen governance for future sustainable biomass production?

The research questions are addressed in Chapters 2 through 5. Table 2 gives an overview of the chapters of this thesis and how they address the three research questions.

Table 2 Structure of the thesis.

Chapter	Topic	Spatial and temporal focus	Energy crops	RQ1	RQ2	RQ3
2	A review of key international biomass and bioenergy sustainability frameworks and certification systems and their application and implications in Colombia.	Global; Colombia/ current status	Any energy crop	++	+	+
3	The GHG emissions and economic performance of the Colombian palm oil sector; current status and long-term perspectives.	Colombia/ current and future status	Oil palm	++	+++	+
4	GHG balance of agricultural intensification & bioenergy production in the Orinoquia region, Colombia.	Orinoquia/ current and future status	Sugarcane, oil palm, and acacia	++	+++	+++
5	Environmental impacts and economic performance of agricultural intensification and bioenergy production in the Orinoquia region	Orinoquia/ current and future status	Sugarcane, oil palm, and acacia	++	+++	+++
The symbols (+) indicate the level addressed by a chapter of the research question.						

Research question 1 is addressed in chapter 2, 3, 4, and 5. Chapter 2 evaluates the sustainability requirements for biomass production. Frameworks and certification schemes based on the criteria and indicators defined by the Renewable Energy Directive are analyzed. In addition, application, and implications of these requirements in the Colombian context are assessed. The environmental and economic impacts of biomass production is addressed in chapters 3 to 5, analyzing the land use change impacts on GHG emissions, biodiversity, water, and economic profitability. Specifically, chapter 3 estimates the impact of palm oil production on emissions at the national level and in regions where palm oil production predominates. In chapters 4 and 5, the Orinoquia region of Colombia is taken as a case study. These chapters evaluate the production of various energy crops at the regional level and their current impact and potential effects under future scenarios and different levels of agricultural intensification.

Research question 2 is mainly addressed in chapters 3, 4, and 5 where different measures and strategies are evaluated including management practices in cropping systems to reduce emissions (e.g., oil palm), modernization options for food crop, cattle, and the use of surplus land for energy crop production with ILUC prevention. For this, the need for agricultural intensification is raised given increasing demand from different land uses and the current low yields that are reported in the country. Agricultural intensification can contribute to producing more food, feed, and biomass within the same amount of agricultural land that is already in use today. This is especially true for extensive cattle production, where increased yields are key to freeing up land that can be used for other purposes such as agriculture or sustainable biomass production. Moreover, chapter 2 identifies strategies for the oil palm sector to work on sustainability of palm oil production and its value chain with a specific focus on the reduction of GHG emissions and economic performance.

Research question 3 is mainly addressed in Chapter 4 and 5, with a general review carried out in Chapter 3. For the analysis of environmental and socio-economic indicators, several analytical frameworks are considered, and methods are combined to quantify the impacts of land use on emissions, biodiversity, water, and the economy. Different scenario analysis and the use of several agricultural improvement practices to minimize impacts and increase agricultural yields are also included. In chapters 4 and 5, an integrated analysis of the effects of agricultural intensification and bioenergy production on GHG emissions, biodiversity, water, and the economy of the region is applied.

1.5 Case study description—key characteristics of Colombia and the Orinoquia region

Colombia is a tropical country located in the continent of South America. The country has been declared one of the most biodiverse countries in the world because of the existence of a wide variety of species (fauna and flora) and natural landscape ecosystems (Moreno et al., 2016). In Colombia, agricultural activity is recognized as the main occupation (61%) of the inhabitants of populated and rural centers (MADR, 2016b). The Colombian agricultural sector accounts for approximately 7% of the country's total gross domestic product (GDP) (MADR, 2016b). Over the past few decades, Colombia's GDP has more than tripled from a value of USD 100 billion in 2000 to USD 331 billion in 2018, thereby highlighting the rank of Colombia as the fourth country with considerable economic progress among the largest economies in Latin America (FAO, 2021).

Colombia ratified the Paris Agreement (UN, 2015) and reported mitigation initiatives in its plan for nationally determined contributions (NDC) to reduce its GHG emissions by 20% by the year 2030, using the 2010 national emissions inventory as the starting point (IDEAM et al., 2018). However, in the year 2020, the country vowed to further reduce its emissions by the year 2030 to a value that would be 49% less than the value of GHG emissions in 2010 (Gobierno de Colombia, 2020b). The country commits to implementing mitigation actions to reduce GHG emissions through the 1) reduction of land use changes and 2) improvement of agricultural production methods and reduction of methane emissions associated with cattle production. Additionally, the country also plans to implement adaptation actions to tackle climate change, such as protection of water resources, ecosystems, and biodiversity (Gobierno de Colombia, 2020b).

Colombia is one country in Latin America that has recently displayed regional leadership in developing dedicated bioeconomy strategies and in strengthening policies that support the sustainable development of the bioenergy sector (García Arbelaez and Gonzáles, 2017) (DNP and Enersinc, 2017). In recent decades, Colombia has reported an increase in the role of bioenergy in reducing the use of fossil fuels by adopting a series of laws that promote the production and use of bioenergy (Law 693/2001, Law 939/2004, and Law 1715/2014). Presently, the use of bioenergy is limited to the production of first-generation biofuels from sugarcane and palm oil (Eras et al., 2019) (UPME, 2019), with 10% blending each (Fedepalma, 2019). The use of biomass for the production of bioelectricity remains marginal (Eras et al., 2019). Sugarcane bagasse is the largest biomass source reported, accounting for approximately 2% of the national electricity production (DNP and Enersinc, 2017) (MX, 2020).

In the near future, diversification of the national energy matrix is expected based on the use of multiple biomass types (e.g., oil palm, wood, and crop residues) (UPME, 2019). This will help reduce dependence on fossil fuels and vulnerability to hydrological fluctuations (ENSO) because 66% of the country's electricity is generated by hydroelectric plants (Eras et al., 2019). Moreover, nearly 52% of the country's area demonstrates the existence of non-interconnected zones to the national grid. Thus, they mainly obtain energy supplied in the form of fossil energy. Therefore, there exists potential to increase bioelectricity generation in such areas to supply electricity (Eras et al., 2019). The national government projects a decrease in the contribution of fossil fuels (diesel and gasoline) to the transportation sector from 95% in 2019 to 76% in 2050. This projected decrease is based on an increase in the electrification of the transportation fleet, where electricity is expected to be generated from bioenergy (UPME, 2019).

Based on landscape and species diversity, the country is divided into six regions based on their natural characteristics (Figure 1). As mentioned above, the Orinoquia region specifically has been deemed a key area for national agricultural development in the coming years. Additionally, the region is fundamentally important for nature conservation (UPRA, 2016) (CIAT & CORMACARENA, 2017). The Orinoquia region possesses expansive areas of native savannas that usually support wetlands; its transformation to agricultural or energy crop production may exert substantial burdens on biodiversity and ecosystems in the region (Gilroy et al., 2015) (López-Ricaurte et al., 2017) (Ocampo-Peñuela et al., 2018) (Pardo and Ocampo-Peñuela, 2019). Thus, an increase in food and non-food demand in the region also poses a challenge for the agricultural sector, as this increased demand must be satisfied in harmony with the conservation of the country's natural heritage and biodiversity (Prüssmann et al., 2020).

Figure 1. Geographical location of Colombia and its regional division according to the natural characteristics of each area. Based on (Rincón et al., 2014).

Of the total area of Orinoquia region (see Figure 2), 39% is considered prohibited areas for agricultural activities and 61% are recognized as lands for agricultural purposes (UPRA, 2018). Presently, approximately 6.4 Mha land area is utilized as pasture for cattle production and 0.6 Mha is utilized as cropland, where the most dominant crops in terms of cultivated area include oil palm (33%), rice (32%), plantain (14%), corn (10%), soybean (7%), and cassava (3%) (Agronet, 2019). Land area of 8.5 Mha, which consists of flooded savannas and shrublands, is available for agricultural production (Agronet, 2019). However, a considerable portion of the land within the available 8.5 Mha land area mainly consists of natural vegetation (UPRA, 2018). Therefore, using this land for agricultural production will most likely result in high LUC-related GHG emissions and may exert negative environmental impacts (CIAT & CORMACARENA, 2017).

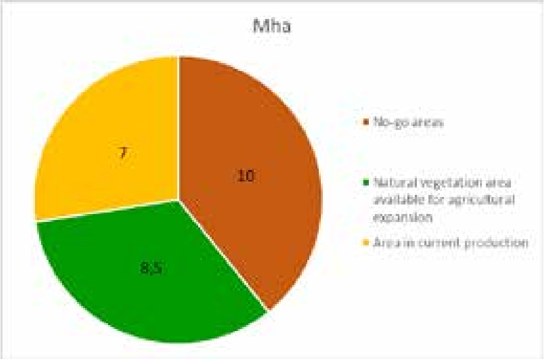

Figure 2. Land distribution in the Orinoquia region. Total area of the region is 25.5 Mha. No-go areas or prohibited areas include natural forests, national parks, indigenous areas, archaeological heritage areas, and the ecosystem transition between the Amazonian and the Savannas (UPRA, 2018) (CIAT & CORMACARENA, 2017) (Agronet, 2019).

1.6 Thesis outline

Chapter 2 analyses the key sustainability certification frameworks for biomass and bioenergy. The analysis includes a review and analysis of the certification systems available at the international level to identify the relevant sustainability criteria for Colombia (social, environmental, and economic) applicable to biomass and its applications for energy and material purposes. The guideline for the analysis was the Renewable Energy Directive (RED 2009/28/EC), updated in 2015 as the Directive (EU) 2015/1513. This chapter provides the improvements that have been made in sustainability frameworks to reduce the social, environmental, and economic impacts of biomass and bio-based product production. Moreover, this chapter identified drivers of environmental, social, and economic issues in Colombia that could affect the establishment of a sustainable bio-based economy (bioeconomy). Although Colombia is already on track to have a sustainable biobased economy, it faces great challenges such as the implementation and compliance with all the laws that have been generated in recent years in the country. In addition to continuing to develop government incentives to promote the use of biobased products, and to use appropriate sustainability indicators (e.g., LUC, ILUC, food security); the generation of trust through good governance and inclusion of sustainable markets are also needed.

Chapter 3 assesses the greenhouse gas emissions and economic performance of the palm oil sector in Colombia by analyzing the current situation of the sector and two potential future scenarios. The assessment includes the production of biodiesel from crude palm oil; biogas from POME; electricity from fiber and shell; compost from several byproducts; and pellets from several byproducts of oil palm. This chapter presents data collection of 70% of the total national production of fresh fruit bunches (FFB). The current situation of crude palm oil production in Colombia is analyzed, including 1) GHG emissions, 2) net energy ratio, and 3) economic performance. For this, the information was collected directly from the palm oil producing companies nationwide. The analysis includes two future scenarios, where the crude palm oil production chain is optimized to reduce GHG emissions.

Chapter 4 analyses the GHG emission impact of biomass production in the Orinoquia region in Colombia. This region demonstrates one of the largest areas for potential agricultural expansion in Colombia and is recognized as one of the largest conservation areas with natural savanna vegetation. Agricultural intensification can contribute toward meeting the increasing demand for food and non-food biomass crops, while also establishing space for nature conservation. This chapter assesses the GHG emissions of agricultural intensification and the use of the surplus land for the production of biomass to replace fossil fuels. The GHG balance was evaluated for three agricultural intensification scenarios and a reference scenario, in combination with three bioenergy production routes: ethanol from sugarcane, biodiesel from oil palm, and bioelectricity production from acacia wood.

Chapter 5 provides an assessment of the integrated environmental and economic performance of agricultural intensification and bioenergy production on the resulting surplus land in the Orinoquia region by the year 2030. The analysis is conducted for the same agricultural intensification scenarios as in Chapter 4. The methodology applied and discussed in this chapter is an explorative effort to demonstrate an integrated impact analysis for the whole region considering agricultural intensification and using surplus land for the production of biomass for energy. We analyzed the impacts of the combined changes in land use on species abundance, water use, and economic feasibility.

Chapter 6 synthesizes the main findings of this thesis, provides answers to the research questions and draws conclusions.

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Chapter 2

A review of key international biomass and bioenergy sustainablility frameworks and certification systems and their application and implications in Colombia

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Abstract

This document presents the results of an analysis of the key sustainability certification systems applicable to biomass and bioenergy. A review was made of the state-of-the-art sustainability frameworks at the international level. The improvements that have been made in these standards in recent years to reduce social, environmental, and economic impacts were identified. In addition, it was determined how some of the initiatives analyzed were implemented in a country such as Colombia, where the establishment of a bio-based economy is being carried out. It was noted that most of the certification systems analyzed have been updated in the last two years. The main adjustments made to the standards are based on criteria developed by the European Commission through the Renewable Energy Directive (EU2015/1513). For environmental issues, it was found that the key update was the inclusion of the indirect land-use change (ILUC). Another key issue addressed is the obligation to calculate and publish the GHG emissions generated annually. Social issues have increased the focus on food security of the population regarding local areas of influence such as the price of the family food basket and food supply. Regarding economic issues, the requirement for a business plan is highlighted to contribute to the economic viability of a certified company. Colombia is one of the countries in the world where the basic conditions support a future sustainable bio-based products sector. Not only does the country have a large amount of land suitable for cultivation, but the land does not require the forests deforestation. However, it must be borne in mind that in a megadiverse country like Colombia, a joint effort (integration) is required between the application of strict laws for the protection of natural resources and the use of certification systems for sustainable products.

2.1 Introduction

There is a growing global interest in biomass as a sustainable energy source: the use of biomass for energy and materials is expected to grow over the next 20 years (IPCC, 2011) (Cramer et al., 2007). Biomass-generated primary energy is expected to increase to the equivalent of 1827 Mt of oil by 2030 (12% of total world primary energy demand) (IEA, 2015). The opening of new markets based on biomass (a bio-economy) implies increased investment in research and innovation. These markets can contribute to social development in terms of creating new jobs and food security, however, at the same time, the increase in the use of biofuels and bioenergy, generates new concerns about the use of biomass. These concerns involve indirect land use change (ILUC), negative impacts on biodiversity, greenhouse gas (GHG) emissions, water use, competition between uses of land, and possible pressure on food prices, along with other important socio-economic conditions (van Dam, Junginger, & Faaij, 2010) (Creutzig et al., 2015). It is important to note that these concerns are still present, and if not adequately addressed, could become barriers to the development of bioenergy and biofuels.

In order to reduce the concerns about biomass-use mentioned above, a number of organizations and governments have developed certification systems to define indicators that can be used to reduce negative impacts on the environment, society and the economy. One of the major focuses has been the reduction and prevention of impacts to the environment, but greater attention should be given to the social component because there are still concerns that have not been taken into account especially in the area of food security and well-being of employees and the surrounding community (van Dam et al., 2010). On the other hand, it is understandable that the certified companies expect to receive an economic benefit when marketing sustainable biomass or sustainable bio-based products. In recent years, sustainability criteria and indicators for biomass products have been developed and implemented by the European Commission (EC) and also by some private organizations such as Global Bioenergy Partnership (GBEP), International Organization for Standardization (ISO), and others (van Dam, Faaij, Hilbert, Petruzzi, & Turkenburg, 2009), (Rimppi, Uusitalo, Väisänen, & Soukka, 2016) (Majer & Hennig, 2016) (Garcia-Nunez et al., 2016).

In Latin America, there is considerable experience with generation of bioenergy (Flavin et al., 2014) and Colombia is a key country in Latin America, because Colombia has a potential for agricultural development of biomass as a source of renewable energy. The modern use of bioenergy in the country is currently limited to the production of first-generation biofuels from sugarcane and palm oil, as well as the use of biomass residues to supply own heat and electricity in biofuel production facilities and injecting surplus electricity to the power grid. In 2015, Colombia produced roughly 20 PJ and 8.25 PJ of biodiesel and ethanol, respectively, in addition to 1.85 PJ of surplus bio-electricity (Asocaña, 2016), (UPME, 2016). These volumes represent minor shares of their respective energy sectors, where the final energy consumption in the road transport sector reached 405 PJ while about 197 PJ of electricity was consumed through the national grid (UPME, 2016). The theoretical biomass energy potential in Colombia was estimated between 2007 and 2011 in the range of 210 to 900 PJ. This range included biomass categories from agricultural and forestry residues, biofuels, animal manure and urban waste. By taking into account different factors that may constrain the availability of biomass for energy purposes (e.g. competing uses, ecological and technical constraints), the technical potential was estimated at 36 PJ to 420 PJ (Gonzalez-Salazar, 2016).

The future sustainable potential of biomass supply for energy purposes largely depends on the management system of the agricultural and livestock sectors (Chum et al., 2011). If Colombia pursues highly efficient and intensified agricultural practices, up to 60 Mha of surplus land could become available for energy purposes compared to a business-as-usual scenario (Jimenez & Faaij, 2012). If one quarter of this area is allocated to purpose-grown perennial energy crops (e.g. eucalyptus), up to 4,600 PJ of technical potential could become available by 2050 from this biomass category. By extrapolating future agricultural production and consumption trends to the future, additional 80 PJ to 250 PJ of technical potential may become available from agricultural residues by 2050; excluding residues from sugarcane and palm oil sectors (Younis, 2018). Moreover, forestry residues, animal manure and urban waste may contribute to the technical potential by about 300 PJ, 27 PJ and 14 PJ by 2030, respectively (Gonzalez-Salazar, 2016). Overall, the future technical biomass supply potential in Colombia is significant and may reach up to 5,200 PJ within the next four decades, which is 6.5 folds the current total final energy consumption in the country (Younis, 2018).

Since 2001, the Colombian government has adopted a series of laws to promote the production and use of biofuels and bioenergy (Law 693/2001, Law 939/2004, and Law 1715/2014). These laws have encouraged the cultivation of sugar cane and oil palm for the production of bioethanol and biodiesel respectively, as well as the use of biomass for cogeneration. For instance, in 2017, the sugarcane sector had a 1% share in the national electricity generation (UPME, 2018). Consequently, to continue to expand the use of renewable energy and reduce the fossil fuel use, the government has issued laws (such as Resolution 1283/2016) that provide tax benefits to companies that generate and manage the use of renewable energy in the country (MADS, 2016b). Although Colombia is on the path to sustainability, a route to implement specific criteria and indicators for sustainability in the use of biomass from agricultural crop waste has not yet been defined. This is needed to realize transition from a fossil-based economy to an economy based on biomass (Hess, Lamers, Stichnothe, Beermann, & Jungmeier, 2016).

Therefore, in this work, review and analysis of the certification systems available at the international level were carried out to identify the sustainability criteria applicable to crop residues (biomass) and bio-based products. The guideline for this document was the Renewable Energy Directive (RED 2009/28/EC), which is mandatory for the use of renewable energy in Europe. Because this directive was updated in 2015 (Directive (EU) 2015/1513), to add new guidelines for such as reducing ILUC, limiting the use of agricultural land for energy purposes, and increasing the amount of GHG emission savings (European Commission, 2017b), some voluntary certification systems have also updated their indicators to adjust to the RED.

There were three primary aims of this study. The first was to carry out a state-of-the-art review of key sustainability frameworks for bioenergy at the international level. To meet this goal, their sustainability criteria (social, environmental, and economic) were identified, it assessed their status and improvements over the last five years, and it determined how the sustainability frameworks compare and what their key strengths and weaknesses are. The second aim was to determine how some of the initiatives analyzed have been implemented in Colombia. This is because this country is characterized by an abundance of valuable resources such as natural biodiversity, water, and substantial land available for cultivation. The third aim was to identify drivers of environment, social and economic issues in the country that could affect establishment of a bio-based economy. It should be noted that the initiatives analyzed in this report are among the best known and the European Commission has accepted some of them. The paper has the following structure. First, it discusses the selection of certification systems and the criteria for selecting them. Then, it makes a general description of the systems and their content. Subsequently, it analyzes and compares them from the point of view of environmental, social, and economic criteria, as well as procedures for governance.

2.2 Methodology

To identify and analyze the most relevant certification systems used in the evaluation of products made from biomass (bioenergy, biofuels, biomaterials), a bibliographic review was carried out. First, the list of voluntary certification schemes recognized by the European Commission[1] to meet biofuel sustainability criteria was taken into account. This implies that the standards cover, among others, criteria such as non-use of land with high carbon stock, protection of biodiversity, reduction of GHGs, and protection of water. Following this, the work of several authors who have gathered and evaluated long lists of sustainability initiatives (van Dam et al., 2010) (Junginger et al., 2006) (Diaz-Chavez, Stichnothe, & Johnson, 2016) were reviewed. Third, the initiatives that have been updated in the last five years were identified. Last, the biomass sustainability certifications systems that apply to Colombia were taken into account. Because of the review, eleven certification schemes were selected that include the use of biomass at the agricultural, biofuel and energy levels (see Table 1).

2.3 Data/Review

This section is divided into four parts. In Section 3.1, the strengths and weaknesses of each of the certification systems shown in Table 1 were identified. In Section 3.2, the certification systems applicable to Colombia were discussed. In Section 3.3, the aspects that should be taken into account when planning sustainable biomass production and use were discussed. Specific attention was paid to the conditions in Colombia, where high biodiversity and specific socioeconomic matters are very prominent. In Section 3.4, the use of Good Governance for both certification systems and national governments were discussed.

2.3.1 General Certifications

Table 1 shows the eleven (11) certification systems for sustainable bio-based products or sustainable biomass evaluated in this document. There are ten (10) international certification systems and one certification system specific to Colombia (Icontec-GTC 213).

2.3.1.1 Renewable Energy Directive (RED)

One of the main objectives of the Renewable Energy Directive from the European Union (EU) is to ensure a sustainable production of biofuels (European Parliament, 2016). RED (2009/28/EC) defines the scope for the progressive use of renewable energy in the coming years, through a series of sustainability criteria for biofuels produced or consumed in the EU. Thus, the EU anticipates that by 2020 the renewable portion of energy use will be at least 20% and by 2030, at least 27% (European Commission, 2017b). In addition, in 2015, the RED became more stringent as it required the reduction of GHG emissions caused by indirect land uses with high carbon value. Thus, this directive was adjusted as EU2015/1513 to include GHG estimates for ILUC. The aim was to prevent land intended for food production from being converted to production of biofuels (European Parliament, 2015).

In addition, Article 17 (2) was replaced with “GHG emission saving shall be at least 60% for biofuels produced in installations starting operation after 5 October 2015. In the case of installations which were in operation on or before 5 October 2015, biofuels shall achieve a GHG emission saving of at least 35% until 31 December 2017 and at least 50% from 1 January 2018” (European Parliament, 2015). Any company that is interested in meeting these criteria can demonstrate this through the use of national certification systems or voluntary systems recognized by the European Commission.

2.3.1.2 Better Biomass (NTA 8080-1)

Better Biomass is an international certification system used to evaluate the production of sustainable biomass to generate bio-based products. It is a voluntary scheme under the name NTA[2] 8080. Organizations can use it to demonstrate that the biomass that is produced, processed, marketed, or used is sustainable. The scope of NTA 8080 in the 2009 (first) edition was to produce biomass in a sustainable way for its application in bioenergy; but an increase in the use of biomass

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[1] https://ec.europa.eu/energy/node/74

[2] Netherlands Technical Agreement

by the chemical industry to replace fossil resources led to the updating of the standard. In its second edition, NTA 8080-1:2015, the scope was expanded to demonstrate compliance with mandatory sustainability criteria for application in bioenergy (electricity, heating, refrigeration, and fuel transport) and for bio-based products. Among the adjustments made were: a) inclusion of the use of calculation tools for GHG emissions (Biograce I and Biograce II); b) inclusion of new developments in sustainability aspects such as ILUC and carbon debt; and (c) the certification document was split into two parts, one for sustainability requirements and the other for chain-of-custody requirements (NTA 8080-1, 2015).

Table 3. General characteristics of certification systems included in this overview. • = Included; X= not included.

Level System	Initiative	Principal Scope	Additional Scope	Analyzed publication	Type of scheme	Initiator	EC-RED[3]	GHG tool/method
General Certification	ISCC	Raw materials and products	Bioenergy, food, feed and chemical /technical	ISCC 202. Version 3.0/2016	Voluntary	Multi-stakeholder process	•	GHG emissions calculation methodology
	RSB	Biomaterials	Biofuels, biomass derived products or by-products	Version 3.0/2016	Voluntary	Global multi-stakeholder coalition	•	GHG calculator tool (RSB, Biograce, others)
	Icontec-GTC 213	Biofuel	X	2011	Voluntary	Multi-stakeholder process in Colombia	X	X
Bioenergy Certification	GBEP	Bioenergy	X	First Edition/2011	Voluntary	G8 Leaders	•	Analytical tools
	BETTER BIOMASS	Bioenergy	Bioenergy and bio-based products	NTA 8080-1:2015	Voluntary	The Netherlands Government	•	BioGrace GHG calculation tool
	ISO 13065	Bioenergy	X	2015	Voluntary	G8 Leaders	X	ISO/TS 14067:2013, GHG-Carbon footprint of products
	SBP	Bioenergy	Woody biomass (pellets and wood chips)	Version 1.0/2015	Voluntary	European utilities that use biomass in thermal generating plants	X	X
	EC-RED	Bioenergy	Biofuels and bioliquids	Directive 2009/28/EC amended through Directive EU2015/1513	Mandatory	European Parliament	•	GHG emissions calculation methodology
Agricultural Certification	RTRS	Sustainable soy production	X	Version 3.0/2016	Voluntary	Multi-stakeholder process	•	GHG emissions calculation methodology
	RSPO	Sustainable palm oil production	X	RSPO P&C 2013	Voluntary	Multi-stakeholder process	•	PalmGHG calculator
	BONSUCRO	Sustainable sugarcane production	X	Version 4.2/2016	Voluntary	Multi-stakeholder process	•	Biograce GHG Calculator tool

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[3] EC-RED (European Commission – Renewable Energy Directive)

The NTA 8080-1: 2015 has six principles that refer to: 1) GHG, 2) Competition between food and other local uses of biomass, 3) Biodiversity, 4) The environment, 5) Prosperity, and 6) Wellbeing. Within Principle 2, this standard highlights the use of “ILUC low risk” to demonstrate that the biomass being used does not induce any ILUC. In addition, it is emphasized that the production of biomass for the generation of energy, or its application in bio-based products on existing farmland does not lead indirectly to the conversion of land with high carbon content and/or for agricultural purposes. The standard asks that the Low Indirect Impact Biofuels (LIIB)[4] methodology (or a similar method) be used with its most recent version (1 January 2015), as the reference date. On the other hand, the same principle highlights that Better Biomass requires organizations to monitor local prices of biomass or natural resources that are used to produce biomass and that are crucial for the basic needs of the local population. In addition, it also requires efficient use of biomass, especially that which could be used for both food and non-food-uses (bioenergy, biofuels). In order to comply with this criterion, the use must be justified according to environmental, economic, and logistical considerations.

2.3.1.3 ISO 13065

The International Organization for Standardization (ISO) developed ISO 13065 edition 2015 on sustainability criteria for all forms of bioenergy. This Standard aims to facilitate the assessment of sustainability criteria in the bioenergy supply chain (ISO, 2015a). In this standard, the principles, criteria, and indicators cover the three dimensions of sustainability: environmental, social, and economic. Regarding the environment, aspects such as GHG, biodiversity, soil, water, air, energy efficiency, and waste are covered. At the GHG level, this standard emphasizes the reduction of anthropogenic emissions in bioenergy production. For this, the standard requests the use of the requirements described in clause 6 of the same standard, in conjunction with the use of ISO/TS 14067 (carbon footprint of products). Despite this, the standard clarifies that, if there is any difference between the requirements of ISO/TS 14067 and the requirements of Clause 6, the provisions of clause 6 shall prevail. On the other hand, the principle of "Promote positive and negative impacts on biodiversity" is highlighted, because both the direct operating area and the surrounding protected areas are taken into account (ISO, 2015a).

Another interesting principle in this standard is “Promote efficient use of energy resources.” This principle requires energy balance involving all the energy sources used in the process. The social aspect focuses on respect for human rights, labor rights, the right to use land, and the right to use water (including gain free, prior and informed consent). Finally, the economic aspect focuses on economic sustainability in order to make production and commercialization of bioenergy economical and financially viable (fair business practices and financial risk management) (ISO, 2015a).

2.3.1.4 Global Bio-Energy Partnership (GBEP)

GBEP was started in 2006 to implement sustainability indicators for bioenergy and biomass, and thus contribute to the reduction of GHG emissions and facilitate access to bioenergy (GBEP, 2016). In 2011, GBEP published 24 voluntary sustainability indicators for production and use of bioenergy. These indicators were developed to evaluate the sustainability of production and use of bioenergy. Each indicator is covered by methodology sheets providing the information needed to evaluate the selected indicators. Other situations such as data requirements, data sources, and potential bottlenecks to data acquisition are also described. One of the issues that concern GBEP is food security because food production has a complex and multifaceted relationship with bioenergy. GBEP aims to demonstrate that the production and sustainable use of bioenergy can contribute to both energy and food security. For this reason, the main indicators in GBEP are related to food security: 1) Price and supply of a national food basket, 2) Land use and LUC, 3) Allocation and tenure of land, 4) Change in income, 5) Bioenergy used to expand access to modern energy services, and 6)

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[4] Visit the LIIB certification module website.

Infrastructure and logistics for distribution of bioenergy. This set of indicators is complemented by other indicators that affect food security, such as soil quality, landscape biodiversity, water use and efficiency, and jobs in the bioenergy sector (FAO, 2011).

In order to test the feasibility of the standard as a policy tool, countries such as Colombia, Germany, Ghana, Indonesia, and the Netherlands carried out pilot projects. The pilots varied in the approach adopted, specifically regarding aspects such as the chosen geographic and sectoral scope, and the selection of indicators appropriate within the context of each country. Among the lessons learned, the most important point identified was the availability and quality of relevant data. Data collection methodologies should be improved because some of the required data does not exist or is not reliable (e.g., water quality, GHG, productivity). For example, in some cases, the information available for the indicators was not complete or there simply was no data. In other cases, specific data for bioenergy were available at the regional level but not at the national level. In still other cases, the data were available at the national level but it was not possible to make clear application of the data for the bioenergy sector (Ecofys, 2013).

Situation for Colombia: In the particular case of Colombia, for instance, it was difficult to access specific water quality monitoring data for the bioenergy sector. Another key data issue was the difficulty in implementing the methodology to identify “areas of high biodiversity value” and “critical ecosystems.” It seems that the country did not have a clear definition of these issues at the time, so it was necessary to use a special interpretation during the pilot to complement the indicators (Ecofys, 2013).

2.3.1.5 Roundtable on Sustainable Biomaterials (RSB)

“RSB is an independent and global multi-stakeholder coalition which works to promote the sustainability of biomaterials, including biomass and biofuels.” This standard identifies two types of operators, each one with specific requirements: 1) Biomass Producers (farmers and plantations) and Industrial Operators (feed-stock processors, intermediary producers, and biomaterial producers). The RSB (Biomass Producers) standard has 12 principles and an optional module in which the operators demonstrate that biomass/biofuels/biomaterials were produced using Low ILUC Risk Biomass. The focus of social indicators is to ensure that the production of biomaterials improves local food security and livelihoods in regions of poverty. Environmental certification requires the preservation of biodiversity, as well as best practices in land and water management. The optional ILUC module assumes voluntary compliance, but when combined with the General Principles and Criteria, it allows operators to make a “low ILUC risk” claim. Like the standard NTA 8080-1, the RSB standard is based on the Low Indirect Impact Biofuels (LIIB) methodology. RSB recognizes three approaches for low ILUC risk biomass and biofuels production: Yield Increase, Unused/Degraded Land, and Use of waste/residues (RSB, 2016). RSB Standard has a Certification of Smallholder Groups (RSB-STD-03-002 - version 1.1). This certification allows small farmers to group and work together to access certification. The group must appoint an administrator to maintain communication between all the members. The administration will be responsible for ensuring that all members comply with the requirements of the standard through periodic internal inspections. In addition, the administration will be responsible for establishing an internal management system and ensuring that all group members receive the benefits of the certification (RSB, 2015).

2.3.1.6 Sustainable Biomass Partnership (SBP)

SBP is a standard developed for evaluating woody biomass (pellets and chips) used in industrial energy production. It was created to continue the work of the former Initiative of Wood Pellet Buyers (IWPB). This standard ensures that certified woody biomass is sustainable and contributes to a low carbon economy. In addition, it confirms that the biomass is obtained from legal sources (SBP, 2016). The SBP certification is based on the biomass sustainability criteria of European countries, in particular, the Netherlands, Denmark, Belgium, and the UK. The SBP certification system is founded on two principles: legality and sustainability. Those principles are broken down into 38 indicators of which eight relate to legal sourcing and 30 to sustainable sourcing. Each indicator is rated as either "low risk" or "specified risk." For any indicator rated a "specified risk," the biomass producer must put in place mitigation measures to manage the risk such that it can be considered to be effectively controlled or excluded (SBP, 2015).

This standard does not have a specific indicator to identify GHG emissions, nor a methodology to calculate GHG emissions. The SBP standard specifies "with the exception of an End-User, the Biomass Producer is not responsible for calculating the energy and GHG balance of the supply chain but must provide all necessary data to facilitate those calculations." The information required is that mentioned in SBP standard 6 and SBP 5A (Data collection and communication). In addition, SBP gives as a source of information the link to the page of the European Commission[5], but nothing specific about GHG calculations. Nevertheless, criterion nine has two indicators that discuss maintaining or increasing regional carbon stocks. One of these requires that the raw material not come from areas that had high carbon stocks in January 2008 (wetlands, peatlands). The second indicator requires that the collection of raw materials not diminish the capacity of the forest to act as a sink for storage of carbon in the long term (SBP, 2015).

2.3.1.7 Roundtable on Responsible Soy Association (RTRS)

The Roundtable on Responsible Soy Association, created in 2006, is a voluntary initiative that fosters the growth of sustainable soy production (conventional, organic, and genetically modified), at all scales of production and in all the countries where soy is produced. The RTRS standard has a set of principles, criteria, and indicators that was adjusted in 2016 (version 3), to regulate the process of responsible soy production. RTRS includes key social aspects, such as the disposition to dialogue and communication with local communities on topics related to the activities of its operations and their impacts, or communications for resolving complaints (RTRS, 2016b). To increase the number of producers included in the certification scheme, RTRS designed a methodology that allows producers to start certification in stages for a maximum of three years. Each stage requires compliance with specific indicators. In the first year, the producer must comply with 59 "immediate compliance indicators." In the second year, the producer must comply with 33 short-term indicators. In the third year, the producer must comply with 14 mid-term indicators. At the end of the process, the producer must comply with 100% of the requirements and indicators to obtain certification of its process (RTRS, 2016a).

The RTRS standard (similar to the RSPO standard) developed a version to be applicable at the national level in soy producing countries. This allows the producer country to adjust the indicators to the specific social, economic, and environmental conditions of the country. Furthermore, RTRS has developed an additional voluntary complement called the EU-RED RTRS Compliance Requirements. It will allow soybean producers and processors to meet requirements for the supply of soy-based biofuels to EU member states. However, it is important to note that, given the default values assigned to soybeans, this does not match the savings required by the RED. In practice, this means that some agents in the supply chain will have to record the actual values, together with calculations demonstrating the minimum savings required (RTRS, 2013).

2.3.1.8 Roundtable on Sustainable Palm Oil (RSPO)

The Roundtable on Sustainable Palm Oil was created in 2003 in response to worldwide concern about the negative environmental and social impacts of the rapid expansion of the palm oil sector in Southeast Asia (Espinosa & GTT, 2016). It brings together stakeholders from the seven sectors of the palm oil industry to work towards a global supply of palm oil that meets the criteria of economic,

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[5] http://ec.europa.eu/energy/en/topics/renewable-energy

social, and environmental sustainability. The RSPO Principles and Criteria are developed and revised every five years (RSPO, 2013). In the last update in 2013, four new criteria were included: ethical behavior, no forced labor, respect for human rights, and minimization of GHG emissions from new plantations (Espinosa & GTT, 2016). The RSPO has a specific principle called "commitment to transparency," in which it demands a commitment to ethical conduct in all the activities developed by the producer. A key point to highlight about this certification system is that it has a principle for the responsible development of new plantations. This principle is focused on making an independent and participatory assessment of the technical, social, and environmental impacts, before establishing new plantations or operations. This principle promotes better decision making in order to prevent negative impacts on the project area (location, design, operation) (RSPO, 2013).

The RSPO developed two additional voluntary complements. The first was RSPO-RED for compliance with the RED requirements. The second was RSPO NEXT[6], which was developed in response to the largest market commitments for non-deforestation, no development on peat, no fires, no human rights violations, respect for transparency, and reduction of GHGs. On the other hand, RSPO is in the process of public consultation of the "RSPO Smallholder Strategy", in which new approaches to the certification of excuses for small independent farmers (less than 50 ha) are considered. With this new model, RSPO aims to increase the number of small farmers certified under the standard, guaranteeing compliance with the basic sustainability requirements. The system approach takes into account the needs and reality of the environment based on five key elements that include applicability (who), eligibility (meeting criteria), certification unit (collective work), continuous improvement (phased approach), and small credit producers (incentives for compliance) (RSPO, 2018).

2.3.1.9 Bonsucro (BSI)

Bonsucro, a trade name of Better Sugarcane Initiative Ltd., has developed sustainability indicators for a production standard that applies to any sugarcane farm, mill, or area with which is involved in it (Bonsucro, 2016b). The Bonsucro certification system is made up of five elements: Certification Protocol, Production Standard (including EU), Chain of Custody Standard, Audit Guidance, and Bonsucro Calculator (Bonsucro, 2016a). The production standard has six principles. Principles 1 through 5 ensure that the sugar cane sector complies with legislation, respects human rights, manages the efficiency of the inputs and products, manages biodiversity, and improves key business areas. Principle 6 has an additional mandatory requirement for biofuels under the Fuel Quality Directive (2009/30/EC) and Directive (UE) 2015/1513 (Bonsucro, 2016b). The Bonsucro Calculator is a tool, based on MS Excel, developed to demonstrate compliance with the principles of the standard. Access to this tool is exclusive to Bonsucro members (Bonsucro Secretariat, 2015). The Bonsucro standard also authorizes the use of the BioGrace GHG calculation tool, which is in line with the RED sustainability criteria. Moreover, this tool is recognized as a voluntary scheme by the European Commission (Bonsucro, 2016b).

2.3.1.10 International Sustainability and Carbon Certification (ISCC)

ISCC is an independent multi-stakeholder organization providing a globally applicable certification system for the sustainability of raw materials and products (all types of biomass, including forestry and agricultural, bioenergy, waste and residues, food, feed, and bio-based products). Farms and plantations that produce sustainable biomass must comply with the sustainability requirements laid down in ISCC Document 202 "Sustainability Requirements." The requirements are divided into six principles (ISCC, 2016b). Principle 1 is the strictest and total compliance with the standard and refers to the Protection of "Land with High Biodiversity Value or High Carbon Stock." This principle emphasizes the protection of biodiverse or high carbon areas where threatened or vulnerable species exist. It also covers the legal requirements of the RED as amended by Directive 2015/1513.

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[6] http://www.rspo.org/certification/rspo-next

Failure to meet the requirements of principle 1 related to land use makes the certification approval infeasible. Principle 2 contains the requirements for use of the best agricultural and forestry practices such as soil management, preservation, and requirements for reduction of water pollution. Principles 3 and 4 relate to social requirements for better working conditions and the rights of workers and the community. Principle 5 highlights the legitimacy of the rights of indigenous peoples, especially land rights (ISCC, 2016c).

Requirements pertaining to GHG emission calculations are listed in a document called ISCC-205. This document (ISCC 205) contains the requirements and methodology for calculating GHG emissions for the supply chain. ISCC will require a minimum GHG saving (50–60%) for biofuels as of 2018 (ISCC, 2016d).

2.3.1.11 Icontec GTC-213

This certification system will be analyzed in the next section because it is exclusive to Colombia.

2.3.2 Biomass certification systems applicable to Colombia

Taking into account, the certification systems analyzed previously, in this section it was discuss those that have been applied in Colombia in recent years. Specifically, it was analyzed four standards: the National Interpretation of RSPO (oil palm), Bonsucro (sugar cane), ISCC (carbon certification), and GTC 213 (biodiesel).

2.3.2.1 RSPO-National Interpretation for Colombia

The National Interpretation (NI) of the RSPO 2013 for Colombia was updated in 2016. A Technical Working Group composed of different stakeholder members who were part of the RSPO (growers, processors, industrialists, environmental NGOs and Social NGOs) developed this. Although the NI document has the same Principles and Criteria as RSPO 2013, the Colombian document added seven new indicators. One of those indicators was added to Principle 4, which is about the continuous training of small producers in social-business responsibility and RSPO. Four of those indicators were added to Principle 6, these refer to the adoption of appropriate measures for early education, and standards to ensure that those hired to provide private security are not people who have committed crimes against humanity. Finally, the two indicators added to Principle 7 are related to the training of employees in biodiversity and land acquisition issues. The backbone of the RSPO standard is the application of the principle “free prior and informed consent” of the communities involved with the operation. This principle ensures that certified areas do not present any conflict over land use or land acquisition. In addition, this seeks protection of the collective rights of indigenous peoples and local communities within the national territory. In this context, in Colombia, the relationship with communities is divided into 1) indigenous groups and ethnic groups in general[7] and 2) non-ethnic local groups or communities[8] (Espinosa & GTT, 2016) (Martinez, 2016).

On the other hand, the DAABON Group in Colombia was the first company in the world to be certified under RSPO NEXT. Additional criteria were applicable at the organization level, included investments, joint ventures, and a wider supply base for the organization. This certification included 122 smallholder farms that supply the palm oil fruit to the mill (RSPO, 2017). In some cases, there are economic barriers to the certification of small farmers due to the high costs of certification (Rautner, Leggett, & Davis, 2013), but in Colombia, the RSPO model allows these producers to

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[7] **Indigenous groups and ethnic groups in general**: the relationship is governed by ILO Convention 169, which was ratified by law 21 of 1991 through the figure called "prior consultation". To comply, the law requires the implementation of a series of steps that include ensuring the free, prior and informed consent of the indigenous communities and ethnic groups involved.

[8] **Non-ethnic local groups or communities**: the guidelines indicated in the free, prior and informed consent RSPO guide must be followed, as well as due diligence by producers at all times, in order to respect, mitigate and remedy any impact generated.

benefit from the certification of their crops with the support of the “Núcleo palmero[9]” (group of producers) to which those small farmers belong. This means that the certifications of the large producers cover the small producers as well, therefore, the small producers are not excluded from the system (Hinestroza, 2017). Belonging to a "Nucleo Palmero" is not an obligation; however, the association to a group facilitates the participation of small farmers specially in projects that involve greater quantities of palm fruit production. Technical assistance is another example of the benefits received of the group's joint work (at no additional cost) to increase crop yield through implementing good agricultural practices (Hinestroza, 2017). In a case study carried out in small farmers crops, where the study area was 15% of the palm area in production at nationwide, the implementation of good agricultural practices allowed to increase fruit production by 35% (weighted average in t ha^{-1} $year^{-1}$). Besides the increase in the productivity of those crops, the technologies (good practices) implemented allowed an increase in the efficiency of irrigation (50% less water consumed), the reduction of the incidence of diseases (less use of pesticides) and 8% of the reduction in production costs (Beltrán, Pulver, Guerrero, & Mosquera, 2015).

2.3.2.2 Bonsucro

In Colombia, there are around 225,560 hectares planted in sugar cane in Cauca, Valle del Cauca, and in the south of Risaralda. It is considered a privileged region because it is possible to plant and harvest cane during all the months of the year. The climatic conditions of the region make productivity higher than in other regions of the world (14 t of sugar per hectare per year) (Asocaña, 2017a). Colombia is among the 15 largest sugar producers in the world and produces more sugar than is required for domestic consumption in the country. For instance, in 2016 sugar production was 2.1 million tons, compared to a national demand of 1.6 million tons (Asocaña, 2017b).

At the industrial level, there are 14 sugar mills, of which six companies have associated distilleries for the production of fuel alcohol (Incauca, Manuelita, Providencia, Mayagüez, Risaralda, and Riopaila-Castilla). Over the last 10 years, the Colombian Sugar Sector has become an energy source due to its production of bioethanol and use of cogeneration. As of 2016, the installed capacity of bioethanol production in Colombia was 1,650,000 L/d and the bioethanol blend with gasoline was 6%. Colombian bioethanol reduces GHG emissions by 74%, if compared to gasoline (Asocaña, 2017b). Despite the amount of area planted in the country, Bonsucro has only three member companies (Asocaña, 2017b). The first one is Asocaña, which is the Sugarcane Growers Association of Colombia. The other two companies are Manuelita Group and Riopaila Castilla. The Manuelita group was the first company in Colombia to obtain the Bonsucro certification (October 2017) (Bonsucro, 2016a) and Riopaila Castilla is working on its diagnosis and action plan to achieve the Bonsucro certification (Riopaila Castilla, 2017).

2.3.2.3 International Sustainability and Carbon Certification (ISCC)

In March 2017, three palm oil mills (POM) in northern Colombia received the ISCC certificate: Aceites SA[10], Palmaceite SA[11], and Extractora El Roble SAS[12]. These companies belong to CI Biocosta SA group, an international palm oil trading company, which in 2015 exported 169,766 t of crude palm oil (32.6% of the total exported by the country) (Fedepalma, 2016). All three companies met the RED requirements specified in the ISCC-EU[13] certification system. The certificate[14] issued, specifies that the input material is bunches of fresh fruit (FFB) and that the output material is crude palm oil (CPO)

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[9] "Nucleo palmero" is the grouping of fruit producers (small, medium, and large) and a palm oil mill (POM) close to its area of influence. This business union generates relations of cooperation and trust with a unified approach, thus allowing closing gaps in productivity and reducing production costs. In addition, strategies are developed to timely address phytosanitary risks and threats through comprehensive technical assistance so that group members can benefit.

[10] http://www.aceitesa.com/index.php

[11] http://www.palmaceite.com/

[12] http://www.extractoraelroble.com/

[13] Recognized by the European Commission (EC) to demonstrate compliance with RED and FQD

[14] https://www.iscc-system.org/certificates/valid-certificates/

and crude palm kernel oil (CPKO). Compliance with the requirements of principles 1 to 6 indicates that the biomass produced by these companies is considered sustainable (ISCC, 2016c).

2.3.2.4 Icontec GTC 213

ICONTEC is the Colombian Institute of Technical Standards and Certification. It represents Colombia at international and regional standardization bodies such as ISO. In addition, it belongs to IQNet, the most important international certification network in the world, which promotes the recognition of certificates of management systems in the international arena. Also, ICONTEC is present in different countries of the Americas and the Caribbean and it has 2236 affiliate companies that support the standardization work (ISO, 2017). As an advisor to the National Government in Colombia, ICONTEC has the mission of promoting, developing, and guiding the application of Colombian Technical Standards and other normative documents to obtain an optimum overall economy, improve quality, and facilitate customer-supplier relations at the corporate, national, or international level (Icontec, 2016). One of the standards developed by ICONTEC is standard GTC 213, elaborated through Technical Committee 186, which is chaired by those at Fedebiocombustibles (Fedebiocombustibles, 2011). This standard contains the basic agreements for the participation of Colombia in the development of the different sustainability standards that involve the biofuel sector, such as ISO 13065, where Fedebiocombustibles[15] heads the Colombian delegation (Fedebiocombustibles, 2011).

GTC 213 presents the principles, criteria, and recommendations of environmental, social, and economic sustainability that should be fulfilled in the stages of production and processing of biomass in the biofuels supply chain in Colombia. This does not include other parts of the chain such as transportation, storage, mixing, distribution, and final consumption of biofuels. The guide has 6 principles that include legal compliance, climate change mitigation and GHG reduction, conservation of biodiversity, respect for human and labor rights, economic viability, and commitment to transparency (Icontec, 2011). It should be noted that this guide does not specify indicators but gives recommendations or guidelines for the construction of the indicators. This means that biomass producers and processors must identify the indicators that are appropriate to each of their systems based on the guidelines set out in GTC 213. This type of certification system leads to confusion because each producer should create unique indicators, which will not allow comparisons between producers who obtain certification.

2.3.3 Key Aspects

The eleven certification systems analyzed in this document have more than 50 sustainability criteria/indicators that cover social, environmental, and economic aspects (see Section 4.2). However, this section highlights four of the key methods: ILUC, water, biodiversity, and GHG. These criteria/indicators are paramount in the initial evaluation and design of a project for sustainable biomass production. In addition, the production of sustainable biomass in a megadiverse country like Colombia entails some challenges such as the efficient use of natural resources and the reduction of negative impacts on these resources.

2.3.3.1 Indirect Land Use Change

This is one of the key impacts attributed to the use of biofuels (Abdul-manan, 2017) because the raw materials needed to produce them require water and productive land (Ecofys, RSB, & WWF International, 2012). ILUC occurs when excessive agricultural pressure is applied on lands that are not available for crops (e.g., forests, wetlands) generating GHG emissions (Broch, Hoekman, & Unnasch, 2013). This can have significant impacts on food security (Ecofys et al., 2012). Nonetheless, there is great potential for the production of land-based biofuels, if it is ensured that this is carried out in a sustainable manner (Ecofys et al., 2012) (Brinkman, Wicke, & Faaij, 2017). In recent years,

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[15] Colombia's National Federation of Biofuels

efforts have been made to include this indicator in issues related to the sustainability of bio-based products in some standards. This is the case for RED 2009/28/EC, as amended by Directive (EU) 2015/1513, RSB, and Better Biomass. Table 2 shows the requirements proposed by these three European standards. RSB included an optional module called "Low ILUC Risk Biomass." This module has a set of criteria and compliance indicators for economic operators willing to show that their operations have a low ILUC risk claim (RSB, 2016). Similarly, NTA 8080-1 has an optional compliance indicator to identify ILUC[16]. This emphasizes that the production of biomass should not indirectly affect the conversion of lands with high biodiversity value or high carbon value (NTA 8080-1, 2015). In the European Union, the objectives set out in the RED have been adjusted to reduce the risk of ILUC and to ease issues related to the production of biofuels. The adjustment is specified in Directive (EU) 2015/1513. In addition, "the amendment limits the share of biofuels from crops grown on agricultural land, harmonizes the list of feedstocks for biofuels across the EU and it includes a number of additional reporting obligations for the fuel providers, EU countries, and the European Commission" (European Commission, 2017b).

Table 2. Proposed requirement and databases for Indirect Land Use Change (ILUC) in certification systems.

Initiative	Proposed requirement	Reference
EC-RED	Low indirect land-use change-risk because the feedstocks were produced within schemes which reduce the displacement of production for purposes other than for making biofuels and bioliquids.	(European Parliament, 2015)
BETTER BIOMASS	Possible solutions to reduce the risk of ILUC by the use of biomass: 1) growing biomass on previously unused land 2) additional productivity increase, on top of the trend line (shortening the period that arable land is left fallow; intensifying the use of grassland, increasing the harvest frequency on arable land) 3) integrating existing agriculture or forestry with additional biomass production 4) use of waste and residual flows that had no other application before.	(NTA 8080-1, 2015)
RSB	Low ILUC risk biomass: - Yield increase. Additional biomass was produced through an increase in yield compared to a reference date, without any additional land conversion. - Unused/degraded land. Biomass was produced out of land that was not previously cultivated or was not considered arable land (a reference date is also used). - Use of waste/residues. The raw material used is derived from existing supply chains (e.g., food production, wood processing, etc.) and do not require dedicated production out of arable lands.	(RSB, 2015)

The Better Biomass and RSB standards use the LIIB (Low Indirect Impact Biofuel) methodology to identify the ILUC of raw materials for biofuels. This methodology aims to identify fuels with low indirect risk of impacts in four categories, namely increased yield, unused land, sugarcane-cattle integration, and End-of-life products. Each category analyzes in a particular way the mitigation approaches. For the first category "increased yield", the use of raw materials that have been produced by the increase in crop yield is evaluated. The second category "integration of sugarcane and cattle" evaluates the efficiency of the system with the production of raw materials from the integration of the two mentioned sectors. The third category "unused land" evaluates the use of unused land, with low carbon and low biodiversity, especially in countries with available usable land. The last category "End-of-life products" evaluates, at a regional level, the use of waste that can be used to produce biofuels (Ecofys et al., 2012). On the other hand, although to date, the standards do not have parameters defined for the ILUC, there are some studies that report the risk of ILUC in

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[16] http://www.ecofys.com/en/project/low-indirect-impact-biofuel-methodology/

several European countries (Brinkman et al., 2017) (Gerssen-Gondelach, Wicke, & Faaij, 2017) and Indonesia (van der Laan, Wicke, Verweij, & Faaij, 2017). That studies report that the risk of ILUC can be mitigated through the production of biomass in lands with low carbon reserves, in lands that are no longer used for food and feed production (e.g. 45-62% of total potential), and when there is an increase (improvement) in crop yield (e.g. 32-46% of total potential) (Brinkman et al., 2017) (van der Laan et al., 2017) (Gerssen-Gondelach et al., 2017).

Situation for Colombia: Although to date no specific studies of ILUC have been found in Colombia, some studies have worked in LUC (Romero-Ruiz, Flantua, Tansey, & Berrio, 2012) (Quintero-Gallego, Quintero-Angel, & Vila-Ortega, 2018). The results indicate that changes in land use and coverage have varied as a result of some economic pressures (oil, agro-industry, forestry, livestock, infrastructure) generating changes in the landscape and biodiversity of the country (Romero-Ruiz et al., 2012) (Quintero-Gallego et al., 2018). However, the studies emphasize that in order to continue with sustainable development, it is necessary to preserve areas of ecosystem importance (Romero-Ruiz et al., 2012). Although preserving biodiversity without affecting it is a great challenge, it has been identified that in Colombia it is possible to expand the cultivated areas (land suitable for crops), conserve biodiversity (exclusion areas), and continue with rural development (Ocampo-Peñuela, Garcia-Ulloa, Ghazoul, & Etter, 2018) (Boron, Payán, MacMillan, & Tzanopoulos, 2016).

Colombia has a continental area of 114.17 million hectares, of which 55.4% are non-agricultural use (natural forests, forest reserves, indigenous reserves and collective territories, and mining) and 44.6% are for agricultural use (MADR, 2013). Of the total national land, only 67% is properly used, while 13% is underutilized, and 16% of the land is overexploited (UPRA, 2014). Of the amount of land for agricultural use, 11.3 million hectares correspond to purely agricultural soils, however, only about 4 million hectares are used (MADR, 2013). In recent years the country has worked to organize the management (use) of the national territory through the updating of key instruments for soil management (soil suitability map, soil conflict map, coverages map) (UPRA, 2015). In 2017, the organic carbon map of the country was presented. This map shows that the areas with the highest concentration of this element are in places with agricultural overload (e.g. the Andean region). It is also highlighted that the inadequate use of soil (e.g. tillage, intensive livestock, bad management practices) in the country is a global warming factor that must be monitored to conserve the most carbon-rich areas and implement improvement strategies in the zones of lower concentrations (IGAC, 2017). Colombia has a large land-surface, but agriculture and livestock still have significant yield gaps and potential for efficiency improvement. That means there is a big potential in the country to reduce carbon footprint and to produce additional crops like energy crops (Jimenez & Faaij, 2012). As a result, it is expected the government specifies strategies that guarantee food security, mitigate climate change and protect water resources (IGAC, 2017) (MADS, 2013).

2.3.3.2 Water

Water is used to carry out all kinds of agricultural, industrial, domestic, and environmental activities. Extra water use can generate negative impacts such as degradation of water quality and reduction of the reliability of the water supply (FAO, 2011). In addition, increased demand has made water scarce in many countries (Vázquez del Mercado & Lambarri, 2017). These problems have generated the development of actions for the care and use of water. For example, certification systems have developed monitoring and control criteria and indicators such as availability of water, accessibility, quality, identification, and protection of existing water rights (formal and customary), along with maintenance of areas of natural vegetation around wellsprings and natural waters, among others. RED does not emphasize the indicators to be measured for water sustainability because these requirements consist mainly of good agricultural practices, which at EU level is more effective to address through agricultural policy. However, the European Commission is preparing a report with adjustments to the Directive, which seeks to include measures to avoid excessive water consumption and to increase compliance with the targets set for 2030 (30% energy efficiency) (European Commission, 2017a).

Table 3 shows that all the standards recognize the need for water conservation from three points of view: availability, efficiency of use, and quality. In terms of availability, the watersheds of origin are the focus points for care due to the benefits this provides (Abell, R., 2017). Standards such as ISCC, RTRS, RED, and RSPO have indicators that favor the maintenance and restoration of water protection zones (basins, channels, and watercourses). Even in the specific cases of ISCC and RTRS, the care of natural wetlands is specified. Likewise, respect for water rights is dealt with in RSB, ISCC, SBP, RTRS, and Bonsucro. In terms of efficient use, it is important to consider both the volume of water used and the impacts of its use because both are affected by local conditions such as water availability, water balance, precipitation, temperature, soil properties, and water demand (regarding human beings, agriculture, and nature) (IEA Bioenergy, 2015a). For example, indicators that measure irrigation efficiency in biomass crops or agricultural crops for energy purposes are present in Better Biomass, ISCC, RTRS, GTC 213, and Bonsucro. Other indicators call for the use and monitoring of a water management plan such as RSB, ISCC, SBP, Bonsucro, or RSPO. There are some indicators with more technical or industrial focus that call for measurement of the amount of water consumed per unit of mass (or of product) as in the standards of Bonsucro, GBEP, and RSPO.

Last, water quality may vary depending on the specific type of demand (human, agricultural, environmental, or industrial). For example, quality indices have been established that evaluate the use of water for human consumption, but there are no defined indices for evaluation and use of water for irrigation in crops. However, to ensure that acceptable limits are maintained to allow sustainable end use, the discharge of water from agricultural and industrial activities must be controlled (Misaghi, Delgosha, Razzaghmanesh, & Myers, 2017). In this sense, standards such as GBEP, ISCC, RSPO, RED, RTRS, and SBP take into account the impact of agricultural practices on water quality and call for measurement of parameters such as nitrogen (N), phosphorus (P), and pesticides. Other standards such as Better Biomass and RSPO call for measurement of organic loading (BOD) in effluents. ISO 13065 is more accurate when information is provided about the possible impacts on water quality at the source and in the receiving bodies. This standard calls for identification of key parameters at the physicochemical and biological levels. It also requires the identification of potential impacts such as eutrophication and oxygen depletion.

Situation for Colombia: In general, Colombia is not a country that has a water shortage. It has a watersupply between 1400 and 2300 km^3 $year^{-1}$ (WWF-Colombia, 2012). To take care of this water, there are clear policies to improve water quality and control polluting activities such as industrial and domestic discharges. Discharges affect the water quality when do not comply with the maximum permissible limits of contamination (MADS, 2010). Moreover, there are some additional risks due to contamination such as oil spills, indiscriminate use of agrochemicals, and pollution caused by mining. Due to the aforementioned, the government is taking actions to reduce pollution from the source, encourage clean production and improve the wastewater treatment (MADS, 2010). Resolution 0631 of 2015 makes the report of contamination parameters more stringent. Previous that standard, all productive activities had to comply with a percentage of elimination of contaminant load (kg/day) at a general level, but now, each economic activity must comply with specific maximum limits (mg/l) for each activity. The criteria that must be met include the ranges of admissible temperature, microbiological parameters, a content of active ingredients of pesticides and physicochemical parameters (MADS, 2015b). The greatest demand for the development of socio-economic activities is registered in the agricultural sector (54%), followed by the domestic sector (29%). The greatest water consumption has occurred in regions where water supply is less

Table 3. Overview of environmental principles/criteria and indicators. •= Included; X= not included; ?=Uncertain

Principle/Topic	Criteria/Indicators	Certification System										
		GBEP	BETTER BIOMASS	ISO 13065	RSB	ISCC	SBP	RTRS	EC-RED	BONSUCRO	RSPO	GTC 213
1. Greenhouse gas emissions (GHG) and Carbon Stock	GHG emissions	•	•	•	•	•	?	•	•	•	•	•
	Emissions reduction	X	•	•	•	•	X	•	•	•	•	•
	Biomass is not produced on land with high carbon stock	X	•	?	X	•	•	•	•	•	•	?
2. Biodiversity	HCV areas and risk. (maintain or enhance areas)	•	•	•	•	•	•	•	•	•	•	•
	Ecological corridors	X	•	?	•	•	•	•	?	?	•	•
	Illegal or inappropriate hunting, fishing, trapping or collecting activities are controlled or prohibited.	X	•	?	X	•	•	•	•	X	•	X
	Prevent invasive species from invading areas outside the operation site.	?	•	•	•	•	X	•	?	X	•	?
	Proper use of genetically modified species	X	•	X	•	•	•	•	•	X	X	•
3. Water	Water availability	•	•	•	•	•	•	•	•	•	•	•
	Efficiency of water use	•	•	•	•	•	•	•	•	•	•	•
	Water quality	•	•	•	•	•	•	•	•	•	•	•
4. Air	Air quality	•	•	•	•	?	•	X	•	?	•	•
	Air pollutant emissions reduction (management plan)	X	X	•	•	X	•	X	•	?	•	•
	No open-air burning (residues, wastes, by-products, etc.)	?	•	X	•	•	X	•	?	?	•	•
5. Soil	Soil quality (use of best practices to maintain and improve soil fertility)	•	•	•	•	•	•	•	?	•	•	•

	Land use and land-use change (LUC)	•	•	?	•	•	?	•	?	•	•	•
	Indirect Land Uses Change (ILUC)	?	•	X	•	X	X	X	•	X	?	X
	Maintain in the soil the content of organic matter necessary for its long-term stability (do not remove all residual agricultural products).	X	•	X	•	•	X	X	?	X	•	•
	Biomass/Feedstock is not produced on peatland	?	•	X	•	•	•	?	•	•	•	X
	Restrictions on plant protection products and seeds	X	X	X	X	•	X	•	•	X	X	X
	Avoiding plant protection products by integrated pest management (IPM)	?	X	X	•	•	•	•	•	?	•	•
	Soil surveys and topographic information	X	X	X	X	•	•	•	X	?	•	•
6. Bioenergy	Bioenergy is used to expand access to modern energy services	•	X	•	X	X	X	?	•	•	•	X
7. Waste management	Use of good practices for the storage, handling, use, and disposal of biofuels, fertilizers, and chemicals	X	•	•	•	•	•	•	X	•	•	•

?=Uncertain. This means that the certification system mentions the subject but does NOT define a specific criterion or indicator.

favorable, generating pressures on the resource (availability) especially during periods of extreme weather conditions (MADS, 2010) (CTA, GSI-LAC, COSUDE, & IDEAM, 2015). Because of mentioned before, biomass production clearly also will have to comply with this rule to improve the water quality and water consumption in the country.

2.3.3.3 Biodiversity

The certification systems include several approaches by which to categorize, select, and protect areas with high biodiversity that should not be used in the development of projects (van Dam et al., 2010). Table 3 shows that the standards analyzed bring together five major issues associated with biodiversity. The first describes the need to maintain or improve areas of high conservation value (HCV). The second issue is the use of ecological corridors. In this case, because the fragmentation of landscape and loss of habitat are the main pressures on biodiversity (Immerzeel, Verweij, van der Hilst, & Faaij, 2014), it is important to emphasize that most certification systems require the presence of a criterion to maintain a buffer zone around the project area and to facilitate the movement of wild species. The third issue controls or prohibits illegal or inappropriate hunting, fishing, or harvesting activities. The fourth issue is about invasive species in the production area and the fifth issue is the appropriate use of genetically modified species. In general, standards like Better Biomass, ISCC, and RTRS cover all of the above. RSPO has a principle that specifies "Environmental responsibility and conservation of natural resources and biodiversity." There are six criteria associated with this principle and focused on 1) identification of environmental aspects and management plans, 2) areas of HCV, 3) wastes, 4) renewable energy, 5) fire, and 6) reduction of pollution and emissions (Espinosa & GTT, 2016).

Situation for Colombia: More specifically, Colombia is the second most biodiverse country in the world in terms of ecosystems. For example, forests cover about 53% of the national territory and contain great diversity of fauna and flora and some endemic species, which makes the country highly vulnerable to changes that affect the environment (IDEAM, PNUD, MADS, DNP, & CANCILLERÍA, 2015) (Moreno, Andrade, & Ruiz-Contreras, 2016). This makes Colombia one of the "hotspots[17]" of biodiversity in the world (Critical Ecosystem Partnership Fund, 2015). In addition to this, Colombia has much land available for agricultural use: about 11 million hectares are suitable for the development of new crops, according to the national agricultural zoning map (MADR, 2015). The appropriate zoning and efficient use of the land during the expansion of energy crops poses great challenges, especially for the inclusion of biodiversity indicators in the methodological framework of certification systems for biomass production (IEA Bioenergy, 2015a) (Immerzeel et al., 2014) (UPRA, 2016).

Those in the oil palm sector in Colombia are developing a project to contribute to the conservation of biodiversity and the sustainable management of the palm agroecosystems in the country (called "Paisaje Palmero Biodiverso": Oil palm biodiverse landscape). This project has three specific points: 1) regional planning and guidelines for the conservation of biodiversity, 2) conservation of biodiversity and ecosystem services, and 3) good agro-ecological practices. As a result of this project, it is expected that the oil palm plantations will be planned and managed properly to improve agricultural practices, to avoid contamination of natural resources (water, soil), to incorporate soil cover, to improve the recycling of nutrients, and to retain moisture. In addition, as a contribution to the RSPO certification process, the project is also developing a practical guide to facilitate implementation of the RSPO principles and criteria in the country to, for example, encourage the identification and proper management of HCV, to comply with national regulations, and to protect

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[17] Tropical Andes hotspot located in South America covers much of the territory of Colombia. This Hotspot is notable for its ecosystem services as it is the source of water for the main tributaries of the Amazon and Orinoco rivers and their forests store 5.4 trillion tons of carbon equivalent to the annual carbon emissions of one trillion cars.

the forests and natural ecosystems (Proyecto GEF, 2016) (Fedepalma, WWF, Instituto de Investigación de Recursos Biológicos Alexander von Humboldt, & Cenipalma, 2016).

2.3.3.4 Greenhouse Gas Emissions

At the international level, it is desirable to create a unified methodology for the identification of GHGs (data for calculations) (van Dam et al., 2010). It is known that ongoing efforts have been undertaken to discuss ways to harmonize these efforts. In 2009, a policy-making workshop was held that marked the beginning of the BioGrace[18] Project to harmonize the European calculations of the biofuel GHG emission standards to be met, with the RED and the Fuel Quality Directive (FQD) (Neeft et al., 2012). The BioGrace tool has been recognized as a voluntary scheme by the European Commission (European Commission, 2013). Bonsucro, Better Biomass (NTA8080), and RSB use the BioGrace tool for GHG calculation. Despite this, some certification systems created their own calculation tools. For instance, RSPO has developed and adjusted its own calculator “PalmGHG.” This tool is based on methodology for evaluation of the life cycle of the plantation and the palm oil mill (Bessou et al., 2014). PalmGHG, version 3.0.1 (2016) requires a year of data for the calculation of GHG emissions and it has some predetermined calculations (“biomass to carbon conversion factor, fertilizer sea transport distance, conservation sequestration”), but also provides the potential for users to enter their own values (“LUC emission, POME diverted to compost”) (RSPO, 2013). Moreover, it is interesting that RSPO criterion 7.8 specifies that new plantations should estimate carbon reserves in the soil and vegetation that would be replaced by oil palms, prior to development of the project, to minimize GHG emissions generated by LUC (RSPO, 2013).

Other standards do not have calculation tools but instead have a written methodology that is in line with the RED requirements. ISCC follows the methodology outlined in ISCC 205 to calculate GHG for all elements of the supply chain and to determine emission savings (ISCC, 2016c). The RTRS standard has a methodology that allows soybean producers and processors to comply with the requirements for the supply of soy-based biofuels to member states of the European Union (ISCC, 2016d). In the same context, ISO 13065:2015, paragraph 5.2.1, specifies the requirements to reduce anthropogenic GHG emissions and clause 6 establishes the requirements to quantify the GHG emissions. This clause provides requirements and guidelines to complement ISO/TS 14067 (Carbon footprint of products: Requirements and guidelines for quantification and communication). However, it is specified that if there is a difference in the results from ISO/TS 14067 and those from Clause 6, the Clause 6 results take precedence (ISO, 2015a).

Some frameworks have compliance ranges for GHG emissions and some do not. Regarding the frameworks that include values, RED (EU 2015/1513) specifies that the production of biofuels must have a GHG emission saving of at least 60% (European Parliament, 2015). Better Biomass (NTA 8080-1) mentions the net savings of emissions must involve the entire biomass chain and must be calculated by taking into account the reference fossil fuel. The minimum percentages of savings will be for biofuels 50%, bioliquids 60%, solid and gaseous biomass 60-70% (NTA 8080-1, 2015). RSB, ISCC, and Bonsucro are in line with RED requirements, so the value of emissions savings for biofuels must be met with at least 60% (RSB, 2016) (ISCC, 2016d) (Bonsucro, 2016b). On the other hand, regarding frameworks that do not include default values are ISO 13065, GBEP, SBP, RTRS, and RSPO. Those frameworks only mention the need to express the results in a known and quantifiable unit of measurement (e.g. g CO_2eq MJ^{-1} or g CO_2eq unit $product^{-1}$) (ISO, 2015a) (FAO, 2011) (SBP, 2015) (RTRS, 2016b) (RSPO, 2013). RSPO includes recommendations for development of new low-carbon plantations in such a way that net GHG emissions are minimized. In addition, existing companies must have an action plan to minimize emissions from routine operations (RSPO, 2013).

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[18] www.biograce.net

There are considerations that allow establishing the use of biomass for energy generation to contribute to reducing GHG emissions compared to the use of fossil fuel. This depends on several factors such as the good agricultural practices applied for the crop (fertilization and transport) and most importantly, land use change (LUC). This is because any savings in emissions can be annulled if the LUC were not taken into account at the beginning of the project (Bates, Edgerg, & Nuttall, 2009). For example, according to Abdul-Manan, Malaysian palm oil biodiesel has a low probability (less than 16%) of compliance with the GHG emissions savings specified in RED for 2020. This is mainly due to problems presented by the LUC of oil palm crops in that country. The author also determined that Malaysian palm oil biodiesel has a GHG emission saving between 3.6 and 51.2%, in relation to the figure from the RED fossil fuel comparator (83.8 gCO_2eq/MJ) (Abdul-manan, 2017). As mentioned above, some sustainability standards do not have specific ranges for GHG emissions. For this reason, some case studies are assessed to obtain good examples calculations of complete GHG balances of biofuels. Some examples are listed below. The bioethanol produced with Miscanthus generates less GHG emissions (0 to -78 kg GJ^{-1} ethanol) than the bioethanol of sugar beet (0 to 54 kg GJ^{-1} ethanol), due to the use of land in the Netherlands (van der Hilst, 2012). The production of bioelectricity reports savings of GHG emissions (-395 to 128 g CO_2eq kWh^{-1}) compared to conventional sources (mineral carbon 1000 g CO_2eq kWh^{-1}). While the use of biogas (biomethane) showed savings in GHG emissions (-104 to 51 g CO_2eq MJ^{-1}) compared to gasoline (79 g CO_2eq MJ^{-1}) (Tonini, Hamelin, Alvarado-Morales, & Astrup, 2016). Finally, it has been reported that the GHG emissions generated by the ILUC due to the biofuels production such as sugarcane ethanol, corn ethanol, and soybean biodiesel, are in a range of 10 to 60 g CO_2eq MJ^{-1} (Plevin, Beckman, Golub, Witcover, & O'Hare, 2015).

Situation for Colombia: The situation of oil palm crops, in Colombia, is different from that in Malaysia. In Colombia, oil palm biodiesel is linked to potential reduction of GHG emissions (particularly carbon dioxide) of 83% compared to its fossil equivalent. In the determination of the GHG emissions, the LUC and other considerations such as fertilizers, energy consumed, etc., were taken into account over the entire biodiesel production chain: from cultivation to transportation of the biodiesel to the final destination (Gauch, 2013). On the other hand, in 2016, the country's first GHG inventory report was published. This report presents data for the period 1990–2012. During this period, the forestry (144.2 to 91.1 Mt CO_2eq), agricultural (46 to 66.3 Mt CO_2eq), and transport (18 to 28 Mt CO_2eq) sectors made the greatest contributions to the total emissions of the country, while the largest reductions were achieved by the permanent crops included in the agricultural group (-37 to -44 Mt CO_2eq). Within this period, it is highlighted that in all economic sectors of the country there has been a trend of growing GHG emissions, with the exception of the forestry sector. Since 2005, the latter has reduced emissions, mainly due to the reduction of deforestation. In the agricultural sector, the main GHG emissions come from enteric fermentation (livestock, 37%), and from burning and agricultural land management (34%). The growth of emissions associated with permanent crops (22%) is related to the renewal of coffee, oil palm, and fruit crops (IDEAM, PNUD, MADS, DNP, & CANCILLERÍA, 2016).

Taking into account the national GHG information and the commitments agreed to at COP 21 for GHG reduction, Colombia initiated the development of several strategies. The main strategies were focused on increasing the extension of protected areas and reducing deforestation (MADS, 2016a). Another measure approved was the carbon tax (Article 221, Law 1819 of 2016), which aims to discourage the use of fossil fuels and promote the implementation of more efficient and cleaner energy technologies. For 2017, the value of the tax is about USD 5 for each ton of CO_2 generated by burning fossil fuels, taking into account the CO_2 emission factor of each fuel (Congreso de Colombia, 2016).

2.3.4 Good Governance

The concept and evaluation of sustainability includes not only environmental, social, and economic issues, but also Good Governance. Good Governance includes everything related to policies, regulations, compliance, and evaluation of institutional capacities (Diaz-Chavez et al., 2016). With regard to Good Governance, it was discussed two points. The first point is to provide evidence for the use of good governance in the certification systems, identifying how these were conceived and how it worked. The second point is to show how the national governments are generating public policies that will make the products in Colombia sustainable.

First, Good Governance in certification systems covers the creation and participation of a governance structure. This structure, in general, has a Board of Directors, Assembly, Committees, and Technical Working Groups. In the case of certification systems created under the Roundtable philosophy, joint work with interested parties is also involved (NTA 8080-1, 2015). Table 1 shows that most of the standards evaluated have been generated through a process of consensus building between the stakeholders (private industry, government, NGOs, civil society organizations, etc.). This multi-stakeholder representation often results in a standard with a governance structure made up of a Board of Directors and Technical Working Groups, and which gives equal rights to all the interested parties (Espinosa & GTT, 2016). Similarly, consistency and transparency in standards are key requirements for communicating sustainability results to stakeholders and to the general public. Some standards such as RSB, ISCC, Bonsucro, RSPO, and GTC 213 specify the commitment to transparency within their criteria. EC-RED in Article 24 speaks of a Transparency Platform to make relevant information public (for example, action plans, statistics, reports, and production). At the end of the process and in order to strengthen the credibility of a standard, the process of product certification with the required standard is carried out by accredited independent certification bodies (ISO, 2015b).

In general, the certification systems do not describe the specific process for the selection of the criteria and indicators used. However, GBEP explains that the indicators used in its standard were developed in consensus by a work team. This team developed a list of criteria (themes) taking into account the relevance, the practical sense and the scientific basis. The selected criteria were worked on separately in an environmental sub-group, a social sub-group, and an economic sub-group. At the end of the process, a total of 24 sustainability indicators were obtained, each with a methodology sheet that describes the information analyzed in each indicator (relevance, practical sense and scientific basis) (FAO, 2014). On the other hand, as mentioned above, some standards mention the joint work with interested parties (Roundtable philosophy) and the execution of public consultations prior to the official publication of the final documents. For instance, ISCC specifies some points that must be met in order to a certification system to be transparent. a) the documents must be transcribed into the language of the country of the raw material coming from; b) have published a list of certified operators; c) allow access to the auditor's reports; d) take into account the participation of interested parties before making decisions (public consultation, consultation with indigenous and local communities) (ISCC, 2016a).

Second**,** Good governance regarding public policies. The value and impact of international standards must be recognized by decision-makers (ISO, 2015b), especially in the public sector, because this sector is responsible for using the results of the sustainability assessments to formulate public policies (Diaz-Chavez et al., 2016). The national governments must identify negative social, environmental, and economic impacts and generate policies or laws that reduce the impacts identified for the benefit of the country. For instance, the GBEP standard specifies the importance of measuring indicators transparently and placing them within an appropriate national context, including information on legal, policy, and institutional frameworks (FAO, 2011). GBEP indicators were piloted in five countries (Colombia, Germany, Ghana, Indonesia, and the Netherlands) with the help of FAO and the governments of each country. This was done to test the efficiency in capturing information to measure the sustainability of bioenergy at the national level (Ecofys, 2013).

Situation for Colombia: Colombia was one of the countries selected by GBEP officials to pilot test its indicators to measure the sustainability of bioenergy at the national level. A group of national consultants made up of researchers from the National University of Colombia (UN), researchers from the International Center for Tropical Agriculture (CIAT), and officials from the Ministry of Agriculture and Rural Development (MADR) carried out the pilot test. FAO and international technical experts (Germany) supported this group. During the development of the pilot test, meetings were held between the working group and various stakeholders to analyze the information collected and study the possibility of developing new national policies. One of the results found in that pilot test was that bioenergy produced from cogeneration in sugar mills represents a significant part of the country's total primary energy supply (FAO, 2014). In this context, in recent years, the Colombian Government has adopted a series of measures to promote the production and use of bioenergy (Decree 4892/2011, Resolution 90932/2013, Law 1715/2014) (Cámara de Comercio de Cali, 2016) and to reduce environmental pollution related to the use of biomass (Resolution 909/2008, Resolution 0631/2015). In addition, Colombian officials are working on the formulation of policies to biomass use for the production of renewable energy and bio-based products (MADR, 2016).

2.4 Synthesis and Discussion

In this section, it was discussed the content of the certification systems from two points of view, one general and one at the level of each of the components of sustainability (social, environmental, and economic).

2.4.1 General comments

Most of the certification systems analyzed in this paper (Table 1) have been updated in the last two years. The updates include adjustment of some indicators such as the mandatory reporting of GHG emissions and the inclusion of new indicators such as ILUC and carbon debt. These adjustments are based on Directive EU 2015/1513, which amends Directive 2009/28/EC, which governs the European Union. The GBEP standard is awaiting update because the process started in 2014 (GBEP, 2015). The RSPO was updated in 2013 and is expected to be updated again in 2018. There has been no update for the Colombian standard Icontec-GTC 213 to the present (late 2017).

The methodologies for evaluation of these certification systems show both similarities and differences in the ways in which the sustainability requirements were included. For example, in some standards, indicators are described only generally, and these do not clearly specify what the standard is intended to measure. This is the case of the Icontec-GTC 213 standard and the GBEP standard, where the descriptions of the indicators do not clearly define the requirements to be followed. These rules are limited to giving guidance or description that the reader must interpret. Likewise, the NTA8080: 2009 standard did not have concrete indicators, so it was updated in 2015 to a version called Better Biomass. With the adjustment, concrete indicators were defined that allow better evaluation of the requirements that must be met by organizations. For instance, in the 2009 version, it was only mentioned that the requirements of workers' rights (ILO) should be applied. While in the 2015 version, the working conditions that must be fulfilled are specified (e.g. "The organization shall demonstrate that the local statutory working hours are not exceeded or, if there are no statutory provisions, that a normal working week, without overtime, is not more than 48 hours") (NTA 8080-1, 2015).

Other standards (e.g. RSPO, Bonsucro, and RTRS) that were developed using the roundtable model, designed a methodology for evaluating their supply chains with the help of technical committees of interested parties. Figure 1 shows a key methodology for obtaining sustainability criteria in bio-based products through a certification system. In general, stakeholders involve supply chain actors, consumer goods manufacturers, field experts, social and environmental NGOs, banks, and investors. The group work of technical committees facilitates the evaluation of sustainability indicators attributable to a supply chain. It also allows indicators to be changed according to the needs of stakeholders, although in some cases indicators such as ILUC, GHG, or social well-being may require further research to identify and allocate relative values (Diaz-Chavez et al., 2016). An example of the work of the technical committees of interested parties was developed during the creation of the GBEP standard. The GBEP Standard Working Group developed and agreed upon a list of criteria to be subsequently evaluated. It then established three working subgroups to review the indicators needed for the selected criteria. At the end of the process, decisions were adopted by consensus among partners (FAO, 2011).

Figure 3. Key methodology to obtain sustainability criteria in bio-based products through a certification system (Based on ISO 9001 and [109]).

Another point to mention is the use of a national interpretation document applicable to some of the certification systems (a generic standard) of an international supply chain. In this case, the objective is to cover different national, geographic, and production aspects under the particular conditions of the country where the organization must be evaluated using the generic standard (RSPO, 2007). It must be understood that the generic norm requires that national interpretations must comply with the laws and requirements of international conventions if the country of interpretation has no laws regulating these issues. This type of methodology is used in agricultural certification systems such as RTRS, RSPO, and Bonsucro.

2.4.2 Indicators for Each Area of Concern

For this section, it was analyzed each of the three dimensions of sustainability (social, environmental, and economic) taking into account the indicators present in the eleven certification systems analyzed in this document. The list of indicators is not exhaustive because it was intended that only those most relevant and common to all certification systems be analyzed. A total of 54 sustainability criteria/indicators were identified. Figure 2 shows that, of those criteria or indicators, 44% are related to the environmental issues/aspects, 30% to the social area, and 26% to the economic area. In fact, to date, there is still a greater focus on environmental issues compared to the other issues of sustainability. However, in most certification systems the environmental and socio-economic issues get equal attention.

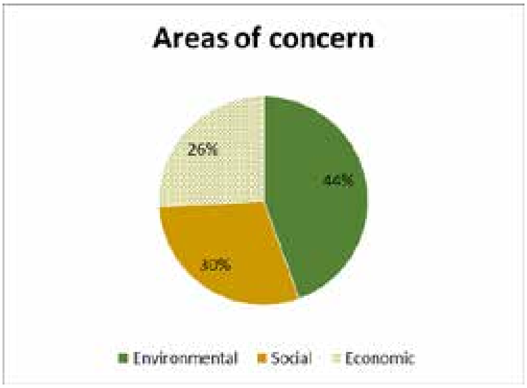

Figure 2. Percentage of participation of sustainability indicators, by areas of concern, included in the eleven certification systems analyzed in this paper.

2.4.2.1 Environmental Aspects

Table 3 shows the seven major principles or topics that were identified in this area. These include GHG emissions and carbon stocks, biodiversity, water, soil, air, bioenergy, and waste management. In total, 24 criteria/indicators, some of which were not included in all the certification systems, were identified. The criteria/indicators present in all standards were soil quality (best practices), areas of high conservation value (maintain or improve at the local, regional, or global level), and water care and conservation (use, efficiency, and quality). On the other hand, the criteria/indicators not consistently present in the standards were phytosanitary products and seeds (restrictions), ILUC, soil survey (topographic), and access to bioenergy. At the global level, the standards with the highest number of indicators for the environmental aspects were ISCC, RED, and RSPO. By contrast, the standard with the lowest number of indicators included in this aspect were GBEP, ISO 13065, and Bonsucro.

There is an interesting indicator in the Better Biomass, RSB, ISCC, and RSPO standards. It refers to the importance of not removing all residual biomass from croplands. It has been mentioned previously that agricultural biomass residues can be used for the development of new products with significant economic benefits, reducing the impact on food security and LUC caused by the production of first generation biofuels (Scarlat, Martinov, & Dallemand, 2010). However, excessive removal of crop biomass could trigger problems with the quality and stability of the soils in the long term. Depending on the particular conditions in the area of agricultural production, it is necessary to retain a certain amount of biomass to sustain soil fertility and to protect against erosion (IEA Bioenergy, 2015b).

In the standards revision, no threshold value was reported for the amount of agricultural waste that must be returned (left) to the soil. The Better Biomass standard only relates the use of BioESoil tool to determine the impact of bioenergy production (loss of nutrients, flow of nutrients returning to the soil) on the crops soil quality (fertility and organic matter). Some studies report the benefit in the use of harvest residues (leaves, trunks, roots) (Beltrán et al., 2015) (Portugal-Pereira, Soria, Rathmann, Schaeffer, & Szklo, 2015) (Romanyà, Rovira, & Vallejo, 2007) but do not relate a specific or general range for compliance in all cases. The amount of biomass that should be left on the field should be evaluated locally. This is because it depends on the type of crop, the climatic conditions of the area, the soil needs, the transport costs of biomass or the competition for the use of biomass in other economic activities (compost, pellets, cogeneration) (Garcia-nuñez, 2015) (Portugal-Pereira et al., 2015). A study in South Africa demonstrated who sustainable residues removal are determined by agriculture methods, soil, and climate. For instance, to control soil erosion it was estimated a minimum biomass requirement of 2 t ha^{-1} (Batidzirai et al., 2016). In Colombia, oil palm cultivation reported the use of pruning leaves and EFB (empty fruit bunches) around the palm to conserve soil moisture, promote root emission and increase nutritional efficiency (Beltrán et al., 2015). While pruning leaves should always remain in the crop (Fontannilla, C;Mosquera, M; Ruiz, E; Beltrán, J; Guerrero, 2015), the dose of EFB application will depend on the cultivation age, the expected production and the specific requirements of the soil (fertilization). For example, for a young palm crop (<7 years) the dose varies between 10 - 30 t ha^{-1}, while for an adult palm crop (>7 years) the dose varies between 35 - 70 t ha^{-1} (Ramirez, Silva, Garzón, & Yáñez, 2011).

Other key concerns are land use indicators. On this point, there are two visions in the standards. The first is about land rights and how were acquired. The second refers to changes in the use of the land where the crop is planted. All standards have an indicator associated with land rights but not all standards have a clear indicator to evaluate LUC. Land use has contributed significantly to increasing GHG levels in the atmosphere (ONU-REDD & Vidal, 2014). For instance, over the past two hundred years, extensive forest areas have been cleared for cereal and cotton production in the United States and Europe, as well as for livestock and plantations of coffee, sugar cane, rubber, tea, and oil palm in Asia, Africa, and Latin America (Martin, 2008). Standards such as RTRS, RSPO and RSB have forest clearing and degradation safeguard indicators. However, these require continuous improvement because there is still no general consensus on what "deforestation-free production" means (Taylor, 2015). As a result, sustainable and responsible forest management requires the use of measurable indicators to identify progress in generating ecosystem services and reducing deforestation. In this way, successful decisions can be made by stakeholders (governments, private sector, non-governmental organizations, donor organizations, researchers, and the public) (FAO, 2016).

Situation for Colombia: The most relevant forestry plans and policies have been generated in Colombia since the 1970s (MADS, 2000). Despite this, there are some natural ecosystems that have been transformed and degraded by deforestation caused by illicit cultivation, open-pit mining, and agricultural production, among others (MADS, 2015a). One of the drivers of the deforestation has been the agricultural sector; however, in the case of oil palm, expansion of this crop in the country has more often arisen by conversion of pastures (51%) and agricultural areas (29.1%) than by conversion of areas of natural vegetation (16.1%) (Castiblanco, Etter, & Aide, 2013). To counteract the damage caused to the environment, in recent years the national government has approved several policies and plans of action. That involves such as 1) "Plan de Nacional de Restauración" (National Restoration Plan), 2) "Politica Nacional de biodiversidad" (National Biodiversity Policy), 3) "Politica Nacional de Cambio Climatico" (National Climate Change Policy), and 4) "Política Nacional para la Gestión Integral del Recurso Hídrico" (National Policy for the Integral Management of Water Resources).

2.4.2.2 Social Aspects

The social aspects (see Table 4) include three major principles/topics: rural and social development, food security and human rights, and labor and land rights. These themes include two indicators in all the certification systems: child and woman labor, and land rights and land use rights (both formal and informal). On the other hand, the indicators that were not consistently included in the analyzed systems were: maintain or improve the local food security of the people directly affected and child education. In this order, the standards with the greatest social focus were ISCC, RSB, and RSPO. In contrast, the standards with the lowest level of consideration of social indicators were GBEP and RED. Food security is not the most discussed issue in these certification systems. According to Neydi Clavijo[19], when the certification system is designed for consideration of products from biomass to be

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[19] Magister in Ecological Agriculture and professor of Faculty of Environmental and Rural studies at the Javeriana University (Colombia).

Table 4. Overview of social principles/criteria and indicators. •= Included; X= not included; ?=Uncertain

Principle/Topic	Criteria/Indicators	Certification System										
		GBEP	BETTER BIOMASS	ISO 13065	RSB	ISCC	SBP	RTRS	EC-RED	BONSUCRO	RSPO	GTC 213
1. Rural and Social development	Jobs related to the sector evaluated/local workers	•	•	X	•	•	•	•	X	X	•	X
	Well-being of employees and families (additional to work rights)	X	?	X	•	•	?	•	X	•	•	•
	Children education	X	X	•	X	•	X	X	X	X	•	?
	Social benefits or encourage the participation of women, youth, indigenous communities	X	•	X	•	•	?	•	X	X	•	•
	Community/worker/interested parties complaints	X	•	X	•	•	•	•	X	•	•	•
2. Food security	Price and supply of a local food basket	•	•	•	•	•	X	•	•	X	?	•
	Maintenance or improve the local food security of the directly affected people	X	X	X	•	X	•	X	•	X	•	•
3. Human rights, labour rights and land rights	Existing land rights and land use rights, both formal and informal	•	•	•	•	•	•	•	•	•	•	•
	Free, Prior, and Informed Consents hall form the basis for all negotiated agreements for any compensation, acquisition, or voluntary relinquishment of rights by land users or owners	•	•	•	•	•	•	•	X	•	•	•
	Training and re-qualification of workforce	•	•	•	•	•	•	•	X	•	•	X
	Payment of legal salary/Fair farming agreements	•	•	•	•	•	•	•	?	•	•	•
	Child and women labour	•	•	•	•	•	•	•	•	•	•	•
	Absence of discrimination	?	•	•	•	•	•	•	•	•	•	•
	Occupational safety and health	•	•	•	•	•	•	•	X	•	•	•
	Freedom of association, the right to organize, and the right to collectively bargain.	X	•	•	•	•	•	•	•	•	•	•
	No slave labor or forced labor	X	?	•	•	•	•	•	•	•	•	•

?=Uncertain. This means that the certification system mentions the subject but does NOT define a specific criterion or indicator.

extracted from large tracts of agricultural crops (monoculture), it is not possible to talk about food security. In this case, other indicators related to human well-being must be available (Clavijo, 2016). For example, access to land, land use, access to energy, household incomes, and food supply and prices. These indicators are related to the four dimensions of food security (availability, access, stability, and utilization) (FAO, 2011). However, it was mentioned that for small growers, it is possible to work with the term “Food self-reliance.” This is the ability to generate sufficient income (economic capacity) through agricultural activities to meet food needs (buy sufficient food) (Clavijo, 2016) (FAO, 2009).

Some previous studies have reported several social indicators that cover different aspects and that have been used in different standards. Nevertheless, there are some social indicators that are less used than others as was mentioned before (gender, food security, children education) (van Dam et al., 2010) (Dale et al., 2013) (van Eijck & Faaij, 2014). A study analyzed a methodology to quantify the socio-economic impacts (GDP, imports, and employment) generated by the production of bio-ethanol (sugarcane) in Brazil. The analysis highlights the need to include the interregional approach to identify more accurately the direct-indirect impacts of a sector in a region. For example, the inputs required for the production of bioethanol can come from the same region (direct) or in some cases from regions outside the area of influence (indirect), generating variations in the regional GDP. Also, the impact (positive/negative) of the use of mechanization in crops since it leads to a reduction in the use of workforce (Herreras Martínez et al., 2013). Not all studies focus on the indirect analysis of impacts, which creates a need to delve into issues that go beyond the regional boundaries of a sector at a social and economic level.

Situation for Colombia: In order to contribute to the improvement of the food situation and nutrition of the entire Colombian population, especially the poorest and most vulnerable, in 2013 the national government published the National Food and Nutrition Security Plan 2012–2014, in compliance with what was established in CONPES 113 of 2008 [125, 130]. On the other hand, according to Miriam Martínez[20], to reduce the risk of negative impacts on the food security of the population close to oil palm plantations, the national interpretation of the RSPO for Colombia added this theme to the guidelines. One of them in criterion 6.1 (fostering local entrepreneurship projects) and the other one in criterion 7.1 (forced displacement and loss of food security of the local population are considered unacceptable). This theme contributes to the credibility of the standard because it requires the evaluation of the social impacts prior to establishing a new plantation or expanding existing ones (Martinez, 2016). Likewise, the RSPO is one of the certification systems with a greater focus on social issues because this contains the requirements of ISO 26000, and in some cases anticipates some additional ones. The RSPO standard demands compliance with the basic legal norms of the country and has a strong focus on human rights and their relationship with communities; for this reason, one of the basic guidelines of RSPO is free, prior, and informed consent. Among the countries that produce oil palm, Colombia has a greater number of regulations on labor issues, protection of ethnic communities, and use of indigenous guards. The latter were added as a result of prior consultation (ILO Convention 169) (Martinez, 2016).

In Colombia, both the national laws and the RSPO standard specify the need to identify the origin of the land upon which the oil palm is to be cultivated. In this regard, Miriam mentions the importance of establishing title to land, or leasing the land, to reduce the possibility of incurring problems such as deforestation or abandonment of crops. In spite of this, in Colombia, some laws have not been sufficiently clear about the titling of some land. In addition, in the last 50 years, Colombia has been subjected to armed conflict that has generated complications for the titling of some lands. For this reason before buying rural land to execute productive projects it is essential to verify: 1) the identity

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[20] Leader of Fedepalma Social Area. Colombia.

of the seller, 2) the physical aspects of the property, 3) current occupation of the property, 4) qualification documents, and 5) the legal conditions of ownership (Martinez, 2016).

Some indicators were created to provide welfare to the local community close to the production unit (company). However, there are some companies to give an extra support to the workers or community. The support includes the supply of drinking water, free educational access, support for the creation of a microenterprise, housing construction, among others. In Colombia, there are companies, which benefit their workers and the nearby community through social management. One example is the Manuelita group that supported the creation of several productive units to increase the average monthly income both to the workers' families and to external families belonging to the surrounding communities. One of that microenterprise was created to make gloves for industrial use, where Manuelita provided the training, provided seed capital for the purchase of equipment and machinery, and at the end of the process, Manuelita group was the main client (Manuelita, 2016).

2.4.2.3 Economic Aspects

Table 5 shows an overview of the economic principle/topic and criteria/indicators identified in the certification systems. The economic areas of concern were divided into three groups: economic viability, legal compliance, and good management practices and continuous improvement. The indicator present in all certification systems was to comply with all applicable laws and regulations (national and international) which include, for example, compliance with the payment of royalties and taxes. The ISCC and RSPO standards have large consideration of this economic area, and the largest number of criteria/indicators proposed. Within the Principle/Topic presented in Table 5 denominated “Economic viability,” the most relevant indicator, for compliance with a certification standard, is to have a business plan or management plan. In this regard, while ISO 13065 requests information on financial risk management, such as procedures to identify possible risks and possible measures to address them; other standards such as ISCC, RSPO, and GTC213 require that the business/management plan reflect a commitment to long-term economic viability. Other indicators such as commitment to transparency and anti-corruption documentation are present in most standards. The goal of these indicators is to build credibility among stakeholders in the supply chain and among certified companies.

The Principle/Topic of “Good management practices and continuous improvement” is present in many of the certification systems analyzed (Table 5). This issue is included in the economic area because the producers of biomass or bio-based products must maintain or improve the processes and conditions of their operations to reduce the use of resources (e.g., materials, supplies, fuel, energy, water, etc.). In fact, an interesting criterion in this topic is continuous monitoring to evaluate environmental, social, economic, and industrial impacts. Certification systems such as Better Biomass, ISCC, SBP, RTRS, Bonsucro, RSPO, and GTC213 include the continuous monitoring of impacts within their standards in order to identify possible positive and negative impacts before or during the projects. After their identification, it is necessary to generate action plans to implement monitoring of the impacts appropriately and in this way, reduce or avoid them as the need arises. Although current certification systems have several social and economic indicators, many lack precise definitions and methodologies for measurement (Dale et al., 2013), or these may be based on qualitative indicators (van Eijck et al., 2014). Therefore, this could be considered a key issue (to work toward continuous improvement) in the certification systems for biomass and bio-based products.

Situation for Colombia: Because the environment cannot be separated from the economy, the national government is promoting a vision of climate finance. This vision allows the incorporation of climate change in the economic and financial planning of the country. In this way, it is expected to

Table 5. Overview of economic principles/criteria and indicators. •= Included; X= not included; ?=Uncertain.

Principle/Topic	Criteria/Indicators	GBEP	BETTER BIOMASS	ISO 13065	RSB	ISCC	SBP	RTRS	EC-RED	BONSUCRO	RSPO	GTC 213
Economic Viability	Business plan/management plan	X	X	•	•	•	•	X	•	X	•	•
	Productivity	•	•	•	?	•	•	X	•	•	•	•
	Value added	•	X	X	X	X	X	X	X	•	X	X
	Change in consumption of fossil fuels and traditional use of biomass	•	?	X	X	•	X	•	X	X	•	X
	Anticorruption documents/activities	X	•	•	•	X	•	X	?	X	•	X
	Commitment to transparency	X	?	X	•	•	X	?	•	•	•	•
Legal compliance	Comply with all applicable laws and regulations of the country in which the operation occurs and comply with relevant international laws and agreements	•	•	•	•	•	•	•	•	•	•	•
Good Management Practices and Continuous Improvement	Documentation system and record-keeping economical/farm/process	X	•	•	•	•	•	•	•	X	•	•
	Continuous monitoring to determine impacts assessment	X	•	•	•	•	•	•	•	•	•	•
	Continuous improvement in activities	X	•	X	•	•	•	•	X	•	•	•
	Information on the use of technologies in operations (proprietary technology and intellectual property rights)	X	X	X	•	X	X	X	•	X	X	X
	Disclose technologies/chemical with hazardous or potentially hazardous	X	X	X	•	•	X	•	X	X	•	•
	Full compliance of subcontractors	X	?	X	?	•	X	•	•	•	•	•

?=Uncertain. This means that the certification system mentions the subject but does NOT define a specific criterion or indicator.

guarantee the necessary flow of public, private, and international cooperation financial resources for adaptation and mitigation of climate change. In Colombia, the existing legal framework includes instruments and incentives to favor public and private investment in climate change. However, to achieve effective finance to address climate issues, it is necessary for Colombia to strengthen other financial mechanisms regarding i) market allowances, ii) compensation fee for air emissions, iii) green bonds, and iv) access to mitigation and adaptation loans. The investments of the productive sector in mitigation and adaptation are of vital importance to achieve development compatible with the changing climate (Rudas et al., 2016). An example is the national energy system. Colombia has a large amount of unconventional renewable resources with which to complement this system. Developing this potential offers the country the opportunity to attract investments that increase access to capital and increase the competitiveness of the electricity sector. Although the government has already generated some tax, tariff, and accounting incentives for investment and the use of renewable resources, only 1% of the country's total energy generation corresponds to cogeneration with biomass (García Arbelaez & Gonzáles, 2017). Therefore, the potential for continued and increased investments in the energy sector of the country involving the use of bio-based products is substantial.

2.5 Conclusions and Recommendations

In this document, it was analyzed (strengths and weaknesses) the key sustainability criteria of 10 international systems for certification of bioenergy. Also, it was analyzed how some of the initiatives have been implemented in Colombia. A key observation of the review is that most of the certification systems analyzed have been updated in the last two years. The most important update is the inclusion of the ILUC theme. The standards that have included, to date, this issue in their requirements is RED, Better Biomass, and RSB. RED included the ILUC to reduce the GHG generated by biofuels and thus prevent excessive use of land destined for food production for the production of biofuels. Both RSB and Better Biomass emphasize that in order to reduce the ILUC, the yield of the crops must be increased (higher yield on less land) and the crop residues must be used to generate new products. Another update includes the obligation to include GHG emissions within the sustainability requirements and to publish these emission records. In addition, the use of GHG calculation tools was highlighted to facilitate homogenization and comparison of the information obtained. BioGrace is a calculator recognized as a voluntary scheme by the European Commission for bio-liquids and biofuels. Finally, it was emphasized that despite requiring greater emphasis on the issue of food security, the certification systems evaluated have already included in their social concerns at least one indicator associated with food (e.g., family basket price, food supply).

It was noted that there is still a greater focus on environmental issues than on a balance among essential sustainability issues. However, social, and economic issues have recently achieved greater importance within the requirements of the standards. The most representative requirements for each area of sustainability are highlighted below.

Environmental: The criteria/indicators present in all the standards were soil quality (best practices), areas of high conservation value, and water care and conservation. All the standards recognize the need for water conservation from three points of view: availability, efficiency of use, and quality; but the ways by which these topics were addressed differed. ISCC and RTRS prioritize the care of natural wetlands to maintain water availability. Better Biomass, ISCC, RTRS, GTC 213, and Bonsucro emphasize the efficiency of water use for irrigation. GBEP, ISCC, RSPO, RED, RTRS, and SBP take into account the impact of agricultural practices on water quality and call for the measurement of parameters such as N, P, and pesticides. ISO 13065 is stricter because it calls for the identification of physicochemical and biological parameters associated with possible impacts, such as eutrophication and oxygen depletion. With respect to biodiversity, it is emphasized that all the standards require maintaining or improving HCV areas. In addition, standards require the presence of ecological corridors to maintain a buffer zone around the project area and facilitate the movement (flow) of wild species. ISCC has a stricter requirement to protect land with HCV or high carbon content.

Social: Although in the last few years, the standards have included a greater number of social indicators within their requirements, it is necessary to have specific methodologies that allow for an accurate quantification of social welfare at the local, regional, and national levels. Even, it is necessary to focus on the indirect impacts to go beyond the regional (sectoral) borders. The main issues in the social context, in the certification systems analyzed, were rural and social development, food security, and human, labor, and land rights. The standards in which social issues had the highest priority were ISCC, RSB, and RSPO. Although the GBEP standard has a strong focus on food security, it does not have specific indicators for issues such as child labor, the welfare of employees and their families, free association, and participation of women and indigenous communities in projects.

Economic: All the certification systems required compliance with all laws and regulations (national and international), which include, for instance, compliance with the payment of royalties and taxes. The ISCC and RSPO standards have substantial consideration of issues in this area, and propose the highest number of economic criteria/indicators. Another issue that was highlighted is the requirement for a business or management plan to contribute to the economic viability of the certified company. In this regard, while ISO 13065 requests information on financial risk management, such as procedures to identify possible risks and possible measures to address them; other standards such as ISCC, RSPO, and GTC213 require that the business/management plan reflect a commitment to long-term economic viability.

In addition to the social, environmental, and economic issues, the issue of Good Governance, both within the certification systems and in the participating national governments, is essential to integrate efforts and achieve sustainable biomass production and sustainable bio-based products. Good governance in the certification systems provides for creation and participation of a governance structure. This structure, in general, has a Board of Directors, Assembly, Committees, and technical working groups. In the case of certification systems that were created with the Roundtable philosophy, joint work with interested parties is also involved. The certification systems designed by consensus among interested parties are RTRS, RSPO, Bonsucro, RSB, and GBEP. The requirement for a commitment to transparency was also highlighted, especially in standards such as RSB, ISCC, Bonsucro, RSPO, and GTC 213. Moreover, RED specifies the importance of transparency, especially in the publication of information needed to strengthen the credibility of the standards.

Some certification systems stand out for having special strengths. 1) RTRS has a special certification scheme that allows the producer, especially small producers, to be certified through compliance with a certain number of short and medium-term indicators within a period of up to three years, until completing all requirements. 2) RSPO includes several key issues such as commitment to the acquisition of legal land for cultivation and the inclusion of a principle with guidelines for the responsible development of new plantations. These are intended to promote better decision making and avoid negative impacts on the project area. 3) Better Biomass, RSB, ISCC, and RSPO all have a specific indicator that refers to the importance of not removing all residual biomass from croplands. This means that the use of a portion of crop residues should be promoted but that the quality of the soil where the crop is grown should also maintained. 4) Some certification systems allow a National Interpretation (NI) of their standards to accommodate different national, geographical, and production aspects under the particular conditions in the country where the producer is certified. Despite the above, there are still issues (weaknesses) in the certification systems that call for greater clarity. For example, although all standards have an indicator associated with land rights, not all standards have a clear indicator for assessing LUC. In addition, some standards should be clearer in their description of indicators, such as the Icontec-GTC 213 standard, which only gives a guide or description of the criteria, forcing the reader to interpret these guidelines and to generate the indicators that he considers appropriate to satisfy the criterion.

Situation for Colombia: Colombia is one of the countries in the world where the basic conditions for a future sustainable bio-based sector are most positive. This country has great natural resources that could be used in a sustainable way. For instance, it has been determined that the country has a large amount of land suitable for cultivation without generating deforestation problems. However, this also presents several challenges when it comes to producing or seeding biomass. For this reason, the national government has worked to provide laws to protect the environment (climate, soil, biodiversity, water), increase the role of renewable energy, reduce GHG emissions, stimulate rural development, and build sectors competitive with a vision of climate finance. In other words, the plan is to incorporate climate change into the economic and financial planning of the country.

It is a major challenge to achieve a sustainable bioeconomy where the agricultural sector has an important role in generating products firsthand. It is important that the market for sustainable biomass products diversify sources of economic development to reduce dependence on chemicals and fossil fuels. In addition, development of a bioeconomy represents an opportunity to address the challenges of food security, climate change, and the generation of clean energy. It should also be borne in mind that in a mega-diverse country like Colombia, the complexity of issues such as biodiversity, water, and soil, require integrated use of rigorous national laws for the protection of natural resources and the use of certification systems for sustainable products. Given Colombia's progress on legislation to address climate change (as reported in this paper), the empowerment of public and private sectors regarding sustainability issues have made them more competitive without their having to neglect environmental and social issues. The most widely used standards in the country are international in origin, such as RSPO, RTRS, and Bonsucro.

Finally, it is necessary to emphasize that despite the new requirements issued by RED (ILUC, mitigation options, and GHG calculation tools), to date very few certification systems have been adjusted to incorporate those aspects. On the other hand, although Colombia is already on track to have a sustainable bio-based economy, it faces great challenges such as the implementation and compliance with all the laws that have been generated in recent years in the country. In addition to continuing to develop government incentives to promote the use of bio-based products, and to use appropriate sustainability indicators (e.g., LUC, ILUC, food security); the generation of trust through good governance and inclusion of sustainable markets are also needed. Finally, at a scientific level, it is recommend continuing with the generation of specific information such as land use data, biodiversity monitoring, improvement in worker well-being, and registration of changes in food security in local areas, among others. This information is basic to complement the national and global databases that companies, and governments can use to continue reducing environmental, social, and economic impacts from the expanded bioeconomy.

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Chapter 3

The GHG emissions and economic performance of the colombian palm oil sector; current status and long-term perspectives

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Abstract

Increasing oil palm plantations, both for obtaining crude palm oil (CPO) and for the production of biobased products, have generated growing concern about the impact of greenhouse gas (GHG) emissions on the environment. Colombia has the potential to produce sustainable biobased products from oil palm. Nevertheless, national GHG emissions have not yet been reported by this sector. Achieving the collection of the total primary data from the oil palm sector, in Colombia, entails a tremendous challenge. Notwithstanding, for this study, the data collection of 70% of the production of fresh fruit bunches (FFB) was achieved. Therefore, current situation of CPO production in Colombia is analyzed, including 1) GHG emissions calculation, 2) net energy ratio (NER), and 3) economic performance. Moreover, the analysis includes two future scenarios, where the CPO production chain is optimized to reduce GHG emissions. Future scenario A produces biodiesel (BD), biogas, cogeneration, and compost; while future scenario B produces BD, biogas, cogeneration, and pellets. The methodology, for all the scenarios, includes lifecycle assessment and economic analysis evaluation. The results show a significant potential for improving the current palm oil production, including a 55% reduction in GHG emissions. The impact of land-use change must be mitigated to reduce GHG emissions. Therefore, a sustainable oil palm expansion should be in areas with low carbon stock or areas suitable/available to the crop (e.g., cropland, pastureland). Avoiding the deforestation of natural forests is required. Besides, crop yield should be increased to minimize the land use, using biomass to produce biobased products, and capture biogas to reduce methane emissions. In the biodiesel production lifecycle, the NER analysis shows the fossil energy consumed is lower than the renewable energy produced. Regarding the economic performance, it shows that in an optimized production chain, the capital expenditure and operational expenditure will decrease by approximately 20%.

3.1 Introduction

Palm oil is considered an economic driver (Thomas et al., 2015) due to its versatility, high productivity (around 3.4 tons (t) crude palm oil (CPO) per hectare (ha)) (EPOA, 2016) (Fry, 2017) (Fedepalma, 2017a), and its lower production cost in comparison to other vegetable oils (Khasanah et al., 2015). Indonesia (10,830 thousand ha) and Malaysia (5,150 thousand ha) are the countries with the largest production with around 78% of the global production area, while Colombia (465 thousand ha) is the fifth-largest oil palm producing country with a 2.3% share of global production area (Fedepalma, 2018a). Given that, currently, the demand for food and bio-based products puts pressure on greater agricultural production, the oil palm sector becomes a key player to help meet some of these demands (Mesa, 2017). Notwithstanding, oil palm cultivation has generated controversy because of the deforestation caused in tropical forests of some producing countries (Ramdani and Hino, 2013) (Khasanah, 2019). The debate focuses on the environmental risks associated with deforestation such as the loss of biodiversity, soil quality, water supply, landscape, land-use change (LUC) and release of greenhouse gases (GHG) emissions mainly by the removal of carbon stock from the soil (Thomas et al., 2015) (Khatun et al., 2017). In addition, the accounting system for GHG emissions, especially bioenergy, has been questioned because it is considered to be carbon-neutral. But to justify the potential to reduce emissions, an analysis of the bioenergy must include the biomass source, the effects on land use, the production process and the emissions from its final use (Searchinger et al., 2009). Then, GHG emissions from bioenergy are representative only when biomass growth and collection capture carbon above the level of what would be sequestered (Searchinger et al., 2009). Therefore, a strong relationship between the GHG emissions and the LUC should be considered, since the LUC that occurs in areas that initially had a carbon stock greater than areas with oil palm plantations, causes a debt of carbon from the aboveground. While establishing oil palm plantations in areas that previously had shrubs or grasslands, debt-free can be obtained (Khasanah et al., 2015). Although oil palm expansion has been associated with deforestation in the lead producing countries (Khasanah, 2019) a different situation has been reported for Colombia, where the oil palm expansion has been associated mainly with the conversion of scrublands, croplands, and savannas (Henson et al., 2012) (Castiblanco et al., 2013) (Castanheira et al., 2014) (Furumo and Aide, 2017).

Several studies have reported the GHG emissions of palm oil production (Kusin et al., 2017). However, those studies have used a variety of assumptions, system boundaries, and functional units to calculate and report the emissions. Taking into account that the emissions of the agricultural sector should be harmonized around the flow of the main product traded (Durlinger et al., 2017), the emissions of the palm oil sector should be reported in tons of CPO. Such is the case in a study regarding two CPO production systems that were analyzed for Malaysia and Indonesia, but emissions were expressed in tons of fresh fruit bunches (FFB) instead of reporting them in tons of CPO (Stichnothe and Schuchardt, 2011). Regarding a study in Thailand however, only the stage of oil palm cultivation was evaluated thus the results were expressed in FFB as the main product marketed (Silalertruksa et al., 2017). Studies have reported the GHG emissions in CPO production for Malaysia and Indonesia (Wicke et al., 2008) (Stichnothe and Schuchardt, 2011) (Lam et al., 2019) have been higher than the emissions reported in studies regarding Colombia (Yáñez et al., 2011) (Henson et al., 2012) (Castanheira et al., 2014) (Garcia-Nunez et al., 2016) (Rivera-Méndez et al., 2017). For instance, a study in Indonesia reported a GHG footprint for the CPO production in a range between 0.7 to 26 t CO_2eq t^{-1} CPO (Lam et al., 2019), while for Colombia a study showed a range between -3.0 to 5.3 t CO_2eq t^{-1} CPO (Castanheira et al., 2014). Nevertheless, there is a consensus on the potential for emission reduction in the oil palm sector worldwide as long as good agro-industrial practices are used. It is based on non-deforestation, landscape and soil management, non-use of high carbon stock land, increase in sustainable yield, and the use of biomass in biobased products (Khasanah et al., 2015) (Garcia-Nunez et al., 2016) (Afriyanti et al., 2016) (Abdul-manan, 2017) (RSPO, 2017) (Woittiez, 2019) (Lam et al., 2019).

Colombia has the potential for sustainable oil palm expansion with zero deforestation to go from 0.5 million hectares (Mha) (Fedepalma, 2018b) to 23 Mha (UPRA, 2018). However, strong guidelines, policies, and criteria are required to promote and regulate natural resources and efficient land use suitable for oil palm crops (Castanheira et al., 2014) (Woittiez, 2019) (Khasanah, 2019). As a result, the national government is working on the zoning of the agricultural and forestry sector to identify the geographical areas suitable for planting and livestock production (UPRA, 2019). It is emphasized that the use of those areas is conditioned to the environmental, socioeconomic and management characteristics of each area and each productive chain (UPRA, 2016). In the Colombian oil palm sector, there is a growing awareness of the environmental and social concerns (Espinosa, 2016) so much so, that the sector has adopted various agreements to improve the sustainability of CPO production (MADS, 2017a). This is in line with the shift to a low-carbon development model in the country to reduce GHG emissions, increase the protected areas, promote sustainable development, and avoid deforestation (Garcia Arbelaez et al., 2016) (MADS, 2017b) (WWF-Colombia, 2017). Although in Colombia, several studies have been done to identify the GHG emission of palm oil production, those are based on a limited number of mills or plantations, but it does not involve the whole production chain of the country. Thus, the primary objective of this study is to evaluate the CPO production chain in Colombia for the *current situation* and for two *future scenarios*. The analysis includes 1) GHG emissions calculation, 2) net energy ratio, and 2) economic performance (net present value, internal rate of return, capital expenditure, and operational expenditure). The assessment of the future scenarios includes the production of biodiesel (BD), cogeneration, compost/pellets, and biogas capture. This document is structured as follows: Section 1 describes the present introduction. Section 2 describes the methodology, scenarios, and data sources. Section 3 shows the results of the mass and energy balance, GHG balance to the national and regional level, and the economic performance. Section 4 offers a discussion, and finally, Section 5 outlines the conclusions.

3.2 Methodology

This study analyzed the GHG emissions and economic performance of the Colombian palm oil sector for the current situation (2017) and for two future scenarios. Moreover, the energy balance of the production chain is evaluated through the indicator Net energy ratio (NER). For the economic performance, the indicators evaluated are the net present value (NPV), internal rate of return (IRR), capital expenditure (CAPEX), and operational expenditure (OPEX). Figure 1 shows a flowchart with an overview of the methodology and the type of results obtained.

Scenarios:

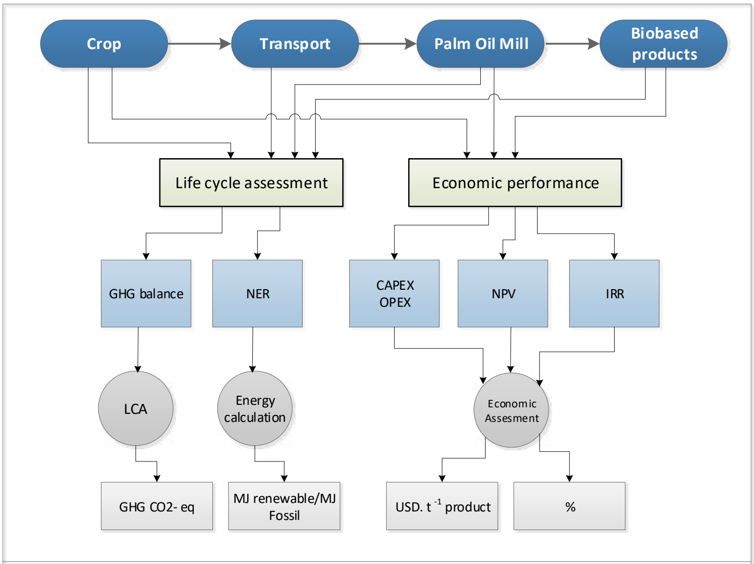
- Current situation. This scenario corresponds to the current status of the palm oil production chain in Colombia (2017), which includes oil palm cultivation, transportation of FFB, and palm oil mills (POMs). Emissions are analyzed at the national and regional scales.

- Future scenarios. A future optimized CPO production is analyzed to minimize GHG emissions and reduce production costs. The future scenarios include cogeneration (see Figure 13 of Annex A.2), compost production, and pellet production (see Garcia-Nunez et al., 2016 to identify other biomass uses). Also, the biogas capture to use as renewable energy is mandatory. Biodiesel production is included since Colombian legislation allows the use of biofuels in the fossil fuel supply matrix for land transport (UPME, 2009). The two future scenarios are described below.

- ***Future scenario A***. The improvements proposed are influenced by an increase in yield, a reduction in the use of chemical fertilizers, LUC mitigation, and value-added biomass production. To mitigate LUC emissions, oil palm must be planted on land with a lower carbon stock such as marginal lands or conventional agricultural land (Wicke et al., 2012) (Castiblanco et al., 2013). However, when it occurs on agricultural lands, it may produce the displacement of the production of food and feed elsewhere (Gerssen-Gondelach, 2015). Therefore, it is essential that land use be complemented by high crops yield to mitigate the

LUC in terms of GHG emissions (Wicke et al., 2012). This scenario includes the analysis of oil palm plantation, FFB transportation, POM, BD plant, cogeneration, and the use of the empty fruit bunches (EFB) in **compost** production.

- ***Future scenario B***. This scenario includes all the conditions mentioned in *future scenario A*; however, in *scenario B*, the EFBs are used to produce **pellets** instead of compost.



GHG	Greenhouse gases	OPEX	Operational Expenditure	MJ	Megajoules
LCA	Life Cycle Assessment	NER	Net Energy Ratio	FFB	Fresh fruit bunches
CO2-eq	CO2 equivalents	NPV	Net Present Value	t	tons
CAPEX	Capital Expenditure	IRR	Internal Rate of return	USD	Dollar

Figure 1. Flowchart of the methodology developed in this study, which shows the stages of the BD chain analyzed per indicator, the indicators evaluated, the method used, and the expected outcomes. Biobased products include BD, biogas, compost, pellets and cogeneration (based on van der Hilst, 2012).

3.2.1 GHG emissions

GHG emission reduction is an important driver of sustainable biobased products; therefore, this indicator is analyzed to evaluate the *current situation* and the future scenarios of the Colombian palm oil sector. Figure 2 shows the system boundaries for each scenario. A detailed life cycle inventory (LCI) is performed using the BioPB[21] model for the CPO production until the mill, while an excel spreadsheet was used to multiply LCI inputs with the corresponding emission factor for the biodiesel production (i.e., physical refining, transesterification, esterification of the free fatty acid (FFA), BD purification, glycerin purification, and methanol recovery). The functional unit 1 t CPO is used since the CPO is considered as the main product of the current oil palm chain in Colombia. The emissions[22] were calculated using the Life cycle assessment (LCA) methodology (ISO 14067),

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[21] BioPB is a model developed by Cenipalma, which contains a database of the Colombian palm oil production chain and its biobased products. This model allows for the calculation of the mass and energy flows within the system boundaries for CPO production of each scenario.

[22] The greenhouse gases analyzed in the CPO production chain were CH_4 produced during the organic degradation of palm oil mill effluent (POME); CO_2 produced along the CPO production chain, and N_2O generated from the managed soil and chemical fertilization of palm cultivation

Intergovernmental Panel on Climate Change (IPCC) guidelines[23], and databases from Ecoinvent and the software SimaPro 8.5. To analyze the impact of LUC on the GHG emissions in the *current situation*, a sensitivity analysis of carbon-stock values from land converted to oil palm was undertaken (see sections 2.4.1).

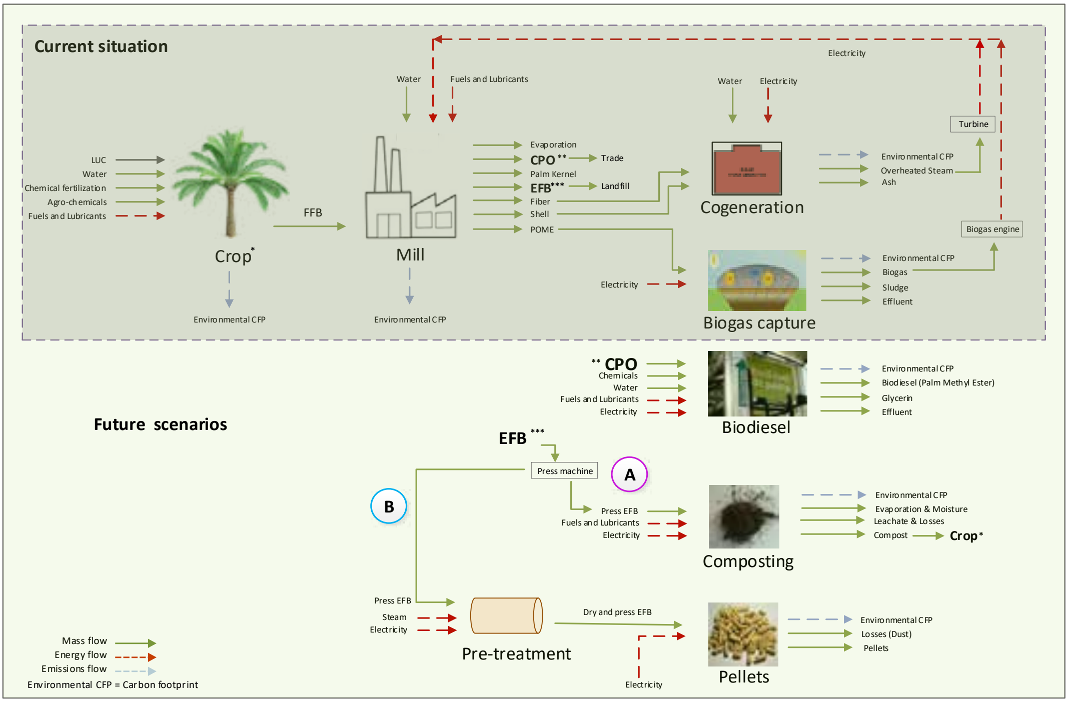

Figure 2. System boundaries for current situation, future scenario A (compost production), and future scenario B (pellet production).

3.2.2 Net energy ratio

The net energy ratio (NER) is an indicator of the life cycle energy balance of a product, which is expressed as the ratio between the renewable energy produced (outputs) and the fossil energy consumed (inputs) (Yáñez Angarita et al., 2009) (Garcia-Nunez et al., 2016). The NER was selected to compare the scenarios. In the *current situation*, the sum of the fossil energy inputs includes the diesel used in cultivation, FFB transportation, and the POM. The sum of renewable energy outputs includes CPO and surplus electricity. In *future scenario A*, fossil energy input includes the diesel used in cultivation, FFB transportation, POM, compost production, and the BD plant. In *future scenario B*, fossil energy input includes the diesel used in cultivation, FFB transportation, POM, BD plant, and pellets production.

3.2.3 Economic performance

To evaluate the economic performance of the palm oil chain, the indicators NPV, IRR, CAPEX, and OPEX are calculated for all the scenarios. The oil palm plantation is assumed to have a lifespan of 30 years. The data collected during the fieldwork (see section 0) and previous studies (Mosquera et al., 2018) were used for the calculations. It is assumed that the CAPEX investment is made in the first year (acquisition costs, purchase of property, machinery, and equipment, etc.). The OPEX includes all

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[23] IPCC equations used: equation 2.1 to calculate annual carbon stock changes; equation 2.5 for LUC emissions; equations 11.1; 11.9 and 11.10 for N_2O emissions.

activities related to FFB production (crop), CPO (mill), and BD plant. The NPV[24] and IRR are used to determine the profitability of the business.

3.2.4 Data sources

The data[25] for this study was collected during field visits to 28 POMs in three Colombian oil palm regions, which accounted for 70% of the FFB processed in 2017 in Colombia. Although in Colombia, there are four oil palm regions, this study is focused on three of them which including the central region (10 mills), eastern region (10 mills), and northern region (8 mills). The southwestern region was not included in this study, as palm oil production was much lower than in the other regions. The data on the production and management of the plantations was obtained from 11 plantations that belong to the owners of certain of the 28 surveyed POMs.

3.2.4.1 Emissions data in the current situation

In the *current situation*, the emissions were calculated individually for each of the 28 POMs. To analyze the regional and national emissions, the average emissions from the 28 mills was calculated. The GHG emissions calculations for each scenario are further explained in the following subsections. In addition, to analyze the impact of LUC on the GHG emissions in the *current situation*, an assessment of the carbon stock values from land converted to oil palm was undertaken.

3.2.4.1.1 LUC in the current situation

Table 1 shows the percentage of areas converted to oil palm at the regional and national scales. The regional scale focuses on an analysis of the three oil palm regions in Colombia, which differ in terms of climate, soil type, land cover, and biodiversity (WWF-Colombia, 2017), and have unique agro-industrial management approaches (Castiblanco et al., 2015) (Henson et al., 2012). Due to the limitations in obtaining complete and recent LUC information, national data (Torres, 2018) and regional data (Castiblanco et al., 2013) were obtained. We assumed that these studies are representative of the type of LUC and carbon stock effects; however, is a degree of uncertainty is present. These studies include the most detailed data available to date (2000-2012). Moreover, our calculations are based on a 30-year plantation lifetime and include both below- and above-ground biomass (oil palm plant, ground cover vegetation, and organic matter). In addition, it is assumed that CO_2 assimilation in the crop occurs in the trunk and in the fronds of the plant; thus the FFBs (CPO, kernel, EFB, fiber, and shell) are regarded as carbon neutral (Wicke et al., 2008).

Table 1. Land use converted to oil palm nationwide and in the three oil palm regions (2000-2012).

Land use/Cover	**% of land cover converted to oil palm**			
	National[a]	**Regional[b]**		
		North	**Central**	**Eastern**
Pastures	45.9	26.0	52.8	68.8
Herbaceous vegetation	19.5	2.4	4.3	1.1
Forests	5.9	3.3	10.9	5.7
Seasonal crops	23.7	4.1	0.2	11.7
Perennial crops	1.4	40.6	6.4	4.3
Heterogeneous agricultural areas	-	23.6	20.0	5.5

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[24] NPV shows the difference between all income and expenses expressed in current currency and IRR considers the expected future returns on investment. The viability of a project is indicated by NPV equal to or greater than zero. The viability of projects must be considered when the IRR is equal to the discount rate and NPV is zero (Sapag and Sapag, 2008).

[25] Primary data is crucial to assess any situation as it allows reducing the assumptions raised, as well as reducing the uncertainty of the results. However, obtaining the total information of a specific sector of a country is not an easy task. Currently, in Colombia, there are about 65 POM in operation and more than 5,000 oil palm plantations, then collecting information from all of them would be a monumental challenge and would require a large investment in both human and economic resources to achieve it. However, for this study, it was possible to collect the primary information of 70% of the country's FFB processed in 2017 (i.e., 28 POM), which is still representative and allows specific and strategic improvements for the whole sector.

Other land covers[c]	3.6	0.0	5.3	3.0

[a]Adapted from (Torres, 2018), who studied official data (i.e. Colombian Institute of Hydrology, Meteorology and Environmental Studies - IDEAM and other government institutions) for the period 2000-2012.

[b]Adapted from (Castiblanco et al., 2013), who presents data from IDEAM, other field data, and satellite data for the period 2002-2008.

[c] This includes urbanized areas, bare soil with sparse vegetation, and water bodies.

3.2.4.1.2 Sensitivity analysis

A sensitivity analysis was undertaken to compare the impact of LUC emissions linked to different values of carbon stock in various land use categories for Colombia. Table 2 shows the land use categories that have been converted to oil palm. Each category has three values of carbon stock found in the literature, which was divided into maximum values, minimum values, and a value defined as "*National*", which is a conservative value used to analyze the impact of LUC emissions in the *current situation*.

Table 2. Carbon-stock values in land use-categories for Colombia.

Land use-categories	t C ha^{-1}		
	National[a]	Min.	Max.
Forest	147.5	48.1[a]	211[c]
Herbaceous vegetation	14.1	14.1[a]	113[c]
Pastures	6.4	6.4[a]	7.4[b]
Seasonal crops	4.2	4.2[a]	33.1[c]
Perennial crops	28.9	28.9[a]	28.9[a]
Heterogeneous agricultural areas	5.8	5.8[a]	5.8[a]
Other land covers (bare soil, sparse vegetation, and water bodies)	0	0[b]	16.4[b]
Oil palm plantations	113[d]	113[d]	129[c]

[a]Data from (Yepes et al., 2011). Carbon-stock value only includes above-ground biomass. Due to the uncertainty in the estimations of GHG emissions associated with the LUC, the IDEAM undertook an estimation of carbon emissions from forest conversion in the country. In addition, reference values for some land uses that are used in this study were designated as "National".

[b]Data from (Henson et al., 2012).

[c]Data from (Castanheira et al., 2014).

[d]Data from (Rivera-Méndez et al., 2017). Carbon-stock value includes palm tree (trunk, fronds, roots), cover vegetation and associated organic matter.

3.2.4.1.3 Plantation management in the current situation

Inputs such as agrochemicals, water, and electricity are included. The nursery stage is not included. Chemical fertilizer application and fuel consumption are considered (i.e. diesel for FFB transport and gasoline used by supervisors). The crop yield is on average 19.3 t FFB ha^{-1} year^{-1} (for more information see A.1).

3.2.4.1.4 POM in the current situation

Fibers and shells are used as fuel in the boiler for steam generation, however, CO_2 emissions from biomass burning in the boiler are not considered since the emissions come from a biogenic source. It is considered 30 t FFB h^{-1} as the POM production scale. Palm kernel oil extraction and palm kernel meal are not considered. Table 4 shows the summary data for this stage. We assumed a CH_4 production rate of 0.36 m^3 CH_4 kg^{-1} COD removed (Yacob et al., 2006). The data collected during fieldwork showed that only eight of the 28 surveyed POMs carry out biogas capture and only four of those generate electricity from biogas (more input data in Appendix A.2).

3.2.4.2 Emissions data in future scenarios

In both future scenarios A and B, the emissions were calculated for a representative study case of the country where the CPO chain is optimized to produce several biobased products. In *future* *scenario A*, the production of BD[26], biogas, cogeneration, and compost are analyzed. While in *future scenario B*, the production of BD, biogas, cogeneration, and pellets are analyzed.

3.2.4.2.1 LUC in the future scenarios

The future emissions generated by LUC due to oil palm expansion must be considered to avoid carbon losses through deforestation. Figure 3 shows a Land Suitability Map[27] for the establishment of oil palm crops in Colombia, as well as the extent of current palm oil plantations (purple areas). In addition, this figure shows the potential new areas for oil palm expansion cover approximately 23 Mha centered in the eastern, central, and northern regions of the country. The dark green areas on the map represent those areas with high potential (5.2 Mha), while light green areas represent moderate potential (10.9 Mha) (UPRA, 2018). The most favorable areas for oil palm expansion are agricultural areas (crops) and livestock areas (pasture areas) (UPRA, 2016) (Castiblanco et al., 2013). It means that indirect LUC must be avoided by the use of suitable land for oil palm and better agricultural efficiencies through the increase of the yields of crops and livestock production (Wicke et al., 2012) (Gerssen-Gondelach et al., 2017). Table 3 shows the LUC and carbon stock for both future scenarios A and B. Note that for future scenario A and B, the same LUC and carbon stock conditions apply. As mentioned before, the only difference between future scenarios A and B is the use of EFB for the production of pellets or the production of compost.

Table 3. Land-use change and carbon-stock for future scenarios.

Land use/covers	% Land-cover converted to palm oil*	Carbon Stock (t C ha^{-1})**
Pasture	60	6.4
Herbaceous vegetation	10	14.1
Seasonal crops	5	4.2
Perennial crops	10	28.9
Heterogeneous agricultural areas	15	5.8

* Data based on the Land Suitability Map from (UPRA, 2018) where the areas suitable for oil palm cultivation correspond to dark green and light green areas in Figure 3. The study by (Castiblanco et al., 2013) was also taken into account to identify the future expansion of oil palm in Colombia.
** National official data from IDEAM (Yepes et al., 2011).
For calculations in oil palm plantations, the oil palm carbon stock is 113 t C ha^{-1} (Rivera-Méndez et al., 2017).

Table 4 shows the primary input data for future scenarios A and B. In addition, it shows a comparison between the data for future scenarios vs. the *current situation*. The transport by trucks from the mill to the BD plant is not considered in the future scenarios since the industrial[28] zone is assumed to be located in the same area. The treated POME is used for irrigation in the nearest plantation to reduce clean water consumption. In the cogeneration stage, steam from the biomass

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[26] BD process involves physical refining (refined, blanched, and deodorized); transesterification; esterification of the free fatty acid (FFA); BD purification; glycerin purification (USP), and methanol recovery.

[27] Land Suitability Map (scale 1:100.000) was developed by *Rural Agricultural Planning Unit of Colombia* (UPRA, 2016) as a national tool for planning efficient land use for sustainable and competitive development. To develop the map, UPRA used multicriteria analysis of physical, environmental, and socioeconomic components weighted according to the characteristics of the palm oil production chain for each area. The map allows for the identification of the geographic areas that present appropriate conditions for the establishment and development of the oil palm. It is highlighted that:

- Unsuitable means areas in which the development of oil palm crops is not feasible due to physical or environmental conditions.
- No development is permitted in areas with legal restrictions.
- Collective territories require a different approach in order to protect the cultural heritage and the right to self-determination of these communities.
- Oil palm crops will not jeopardize natural areas or provision of ecosystem services (i.e. forests, moorland, water bodies, aquifer recharge zones) (UPRA, 2016).

[28] The industrial zone, in future scenario A, includes the area where the POM, BD plant, cogeneration area, and compost production plant are located. The industrial zone, in future scenario B, includes the area where the POM, BD plant, cogeneration area, and pellet production plant are located.

boiler[29] is directed to a backpressure turbine[30] to generate electricity. The surplus steam from the steam turbine is used as saturated steam in the POM and BD plant to supply heat. A low heating value (LHV) of 13.8 MJ kg^{-1} biomass is considered. In addition, a value of 140.6 kWh kg^{-1} steam is considered (Husain et al., 2003). A biogas engine generator is also used to generate electricity (2.2 kWh/m^3 biogas). Air emissions from biogas and power generation are taken into account. Compost application (at a rate of 10% chemical fertilizer application rate) was considered in *future scenario A*.

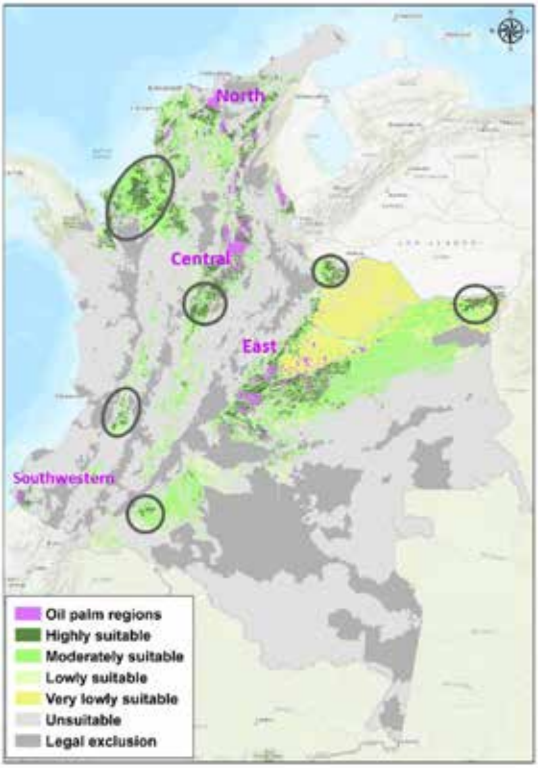

Figure 3. Land suitability map for oil palm crops in Colombia vs current oil palm regions (adapted from *UPRA, 2018)*. Colombia has 114 Mha of which 74 Mha have restrictions for their use (i.e., natural forests, moor areas, riparian buffer zones, water bodies, wetlands, natural parks, urban areas, and cultural protection areas). Which means there are 40 Mha available for agricultural development nationwide (food, feed, livestock and biomass production). This availability is conditioned to low, moderate and high levels of suitability for its use. In addition, of the 40 Mha available, only 7.6 Mha are currently being used nationwide *(UPRA, 2018)*. In 2018, the area planted with oil palm in Colombia was 0.54 Mha (purple areas), of which 41% are sown in the eastern region, 31% in the central region, 24% in the northern region, and 4% in the southwestern region of the country *(Fedepalma, 2019)*. The black circles show some interesting potential new areas for oil palm expansion.

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[29] Boiler conditions: efficiency 79%, 370 °C, and 36 bar.

[30] In Colombia, the backpressure turbine is traditionally used to produce electricity in the POMs, where steam is generated by biomass combustion in a boiler. Then, the residual steam from the turbine is sent to the mill process. In the backpressure turbine, the inlet pressure ranges from 20 to 24 bar and produces up to 50,000 pounds of steam per hour. The turbine steam outlet is about 8 to 10 bar. According to (Arrieta et al., 2007), in a POM, the heat rate is 14 to 60 MJ kWh^{-1}, and depending on the boiler size, the power generated by this system can reach an installed capacity of 1,200 kW with an installation cost of around USD $690-850 kW^{-1}.

Table 4. Summary of the key input data for future scenarios A and B in comparison with the current situation.

Variable		**Current situation** (national average)	**Ref.**	**Future Scenario A and B** (max. value from data collected)		**Ref.**
Primary product		CPO	*	BD		*
Oil palm plantation management						
LUC		Data from Table 1		Data from Table 3		
Crop Lifetime		30 years	*	30 years		*
Crop yield		19.3 t FFB ha^{-1} year^{-1}	*	30 t FFB ha^{-1} year^{-1}		*
Nursery stage		Not included		Not included		
Chemical fertilization		Urea Ammonium nitrate	*	Calcium nitrate		*
Organic fertilization/biomass		No	*	Compost application		*
Palm oil mill						
Installed capacity or scale		30 t FFB h^{-1}	*	70 t FFB h^{-1}		*
Oil extraction yield		21.35%	*	22.11%		*
Biogas capture		32.2% for electricity, 67.8% released into the atmosphere	*	100% used as boiler fuel, biogas engine, and flaring		*
Biomass uses	EFB	No specific use	*	Compost (scenario A), pellets (scenario B)		*
	Fiber	Boiler fuel (steam)	*	Boiler fuel for cogeneration		* **
	Shell	Boiler fuel (steam)	*	Boiler fuel for cogeneration		* **
	POME	Chemical oxygen demand (COD) removal, Discharge to water source	*	COD removal, Biogas for steam, compost production, and irrigation		*
	FFA	No	*	Esterification		*
Biomass pretreatment		No	*	Chopped EFBs (**A**), Chopped and dried EFBs (**B**)		* **
Electricity source	National Grid	47%	*	**Scenario A** 0%	**Scenario B** 10.5%	* **
	Diesel	13%	*	0%	0%	* **
	Cogeneration	30%	*	68.6%	89.5%	* **
	Biogas	9%	*	31.5%	0%	* **

* Production data from the data collected during fieldwork.
** Data from BioPB model (Cenipalma).

3.2.5 Economic assessment data

The FFB production costs are calculated by dividing the total annual cost of one ha of oil palm (includes establishment and maintenance costs) by the volume of FFB produced per ha. For the POMs and BD plants, the production costs of the primary product (CPO or BD, respectively) are calculated by dividing the total annual costs by the volume of product produced per year. Table 5 shows the key parameters to calculate the costs of the CPO production chain. The CAPEX is calculated based on collected data costs or as provided by experts. In the mill, the CAPEX is obtained by multiplying the cost per installed unit (mill production capacity) by the final number of units installed (t FFB h^{-1}). Therefore, CAPEX depends on the scale of the mill and is 30 t FFB h^{-1} in the *current situation* and 70 t FFB h^{-1} in both *future scenarios A and B*.

Table 5. Parameters for the economic evaluation of the palm oil chain in Colombia[a].

Discount rate	12%
Equipment lifetime	30 years
Investment expenditure	100% in first year
Raw material	
FFB	125 USD_{2017} t^{-1} (current s.); 110 USD_{2017} t^{-1} (future sc.)
CPO	735 USD_{2017} t^{-1} (current s.); 646 USD_{2017} t^{-1} (future sc.)
Operational costs	
Plantation costs	*(% of the total crop costs)*
Crop establishment[e]	4%
Crop maintenance	
Fertilization	29%
Harvesting and FFB transport	25%
Agricultural works, supplies, and machinery	22%
Opportunity cost of land	10%
Management costs	10%
POM costs	*(% of the total POM costs)*
Fixed costs	42%
Labor	28%
Equipment and infrastructure maintenance	16%
Electricity	9%
Management costs	5%
BD plant costs[f]	*(% of the total BD plant costs)*
Feedstock	73%
Supplies	21%
Labor	2%
Quality Analysis	1%
Maintenance	1%
Electricity	2%

[a] Parameters came from data collected during fieldwork and the study by (Mosquera et al., 2018). Costs were converted from Colombian pesos (COP) to US dollars (USD) using the 2017 exchange rate (i.e. COP 2,951/1 USD) (http://www.banrep.gov.co/es/trm).

[b] 8% is the real discount rate used by (Mosquera-Montoya et al., 2017), to which we added the average inflation rate for the period 2010-2017 (4%). This yields the 12% nominal discount rate.

[c] In the *current situation*, it is work hours per year obtained from the median collected data.

[d] It is expected that the raw material prices decrease when production yield increases.

[e] This includes crop infrastructure, sowing of palm oil, and coverages, nursery, and others.

[f] Data was taken from (Acevedo et al., 2015). CPO transport from the mill is not considered since the BD plant is assumed to be located in the same area.

3.3 Results

3.3.1 GHG emissions in the current situation

Figure 4 shows the average mass and energy flows of the 28 POMs. The results are expressed in 1 t CPO. In the CPO extraction process, 78% of the fiber and 96% of the shells are used to produce steam and electricity. To run the mill, about 103 kWh of electricity is required; 10% of the electricity came from a biogas engine, 30% from the steam turbine, 13% from an electric generator (diesel), and 47% from the national grid. It can be seen that 68% of biogas is released into the atmosphere (i.e. more than 70% of the mills did not have biogas capture at the time of this study). No specific use for the EFBs was reported according to the survey conducted. Although some mills used EFB as a soil conditioner, it was reported that in most cases this practice is not feasible as the transport of EFB over long-distances is expensive. Consequently, EFBs were commonly sent to the closest landfill, which contributes to additional CH_4 emissions.

The GHG emissions along the CPO production chain, in the *current situation*, are shown in Figure 5. The average carbon footprint is -689.8 kg CO_2eq t^{-1} CPO, where LUC, POME (CH_4), and chemical fertilization are the primary factors contributing to GHG emissions. Eight mills have already eliminated CH_4 emissions from POME through biogas capture and subsequent flaring (four of them generated electricity using biogas). The CH_4 emissions ranged between 357.4 and 1,588.4 kg CO_2eq t^{-1} CPO. This wide variation shows the differences in the efficiency of COD-removal within the POME treatment systems caused by the organic matter content and lagoons system operation (e.g. residence time, presence of bacteria, and the removal of sediment). The survey revealed that the initial COD of the POME ranged from 19,000 to 97,777 ppm (mg l^{-1}) while COD at the point of discharge ranged from 165 to 16,572 ppm. Resolution 631/2015, from the Colombian Ministry of Environment, established permitted levels for pollutant concentrations in wastewater discharge which must be met by the POMs (MADS, 2015). The improvement of efficiency of COD-removal should be considered since in the resolution, the maximum COD threshold allowed is 1,500 ppm at the point of discharge.

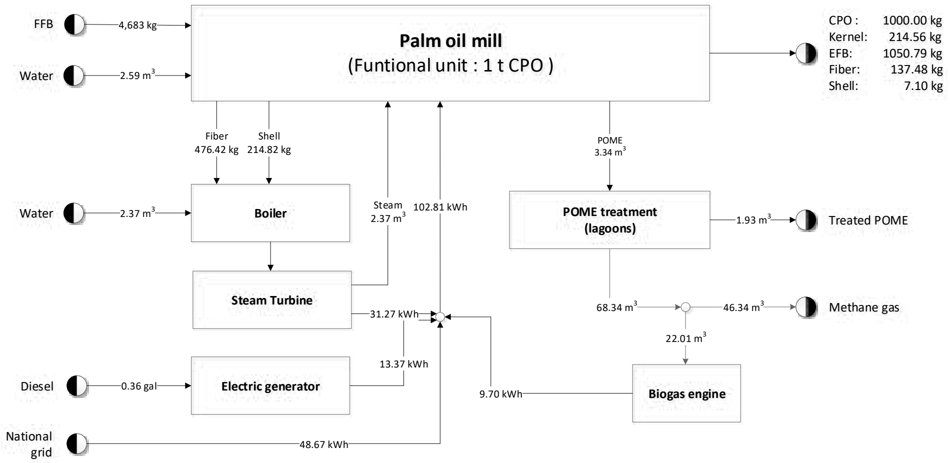

Figure 4. Mass and energy flows in the current situation (CPO production chain).

Figure 6 shows the regional contributions to national GHG emissions. The central region had the highest LUC emissions, while the eastern region had the lowest. In the Colombian eastern region, pastures and seasonal croplands were predominately converted for palm oil production, while in the central region, most land conversions affected pastures (52.8%) and forests (10.9%). A large increase in LUC emissions results from the conversion of forest to arable land. The eastern region is characterized as having the largest number of POMs with biogas capture from the lagoons (five mills of the 28 mills surveyed) which contributes to about 35% reductions in CH_4 emissions.

3.3.1.1 Sensitivity analysis

Table 2 indicates the data used for carbon stock values per land use category, which was used to determine the contribution of LUC emissions. The emissions generated in the rest of the CPO production chain (fertilization, POM, diesel consumption, agrochemicals, and POME) were taken from the calculations of the national average or *current situation*. Figure 7 shows that the carbon stock value directly influences LUC emissions, contributing 16% - 28% of the total emissions. This point to the importance of using specific carbon stock values from areas converted to palm oil. For example, using the maximum and minimum values of carbon stock assumed for oil palm plantations, the LUC emissions ranged from 327 to 695 kg CO_2eq t^{-1} CPO (purple bar), with a carbon stock of -3 to -3.4 t CO_2eq t^{-1} CPO. The negative value indicates a net carbon capture in oil palm plantations.

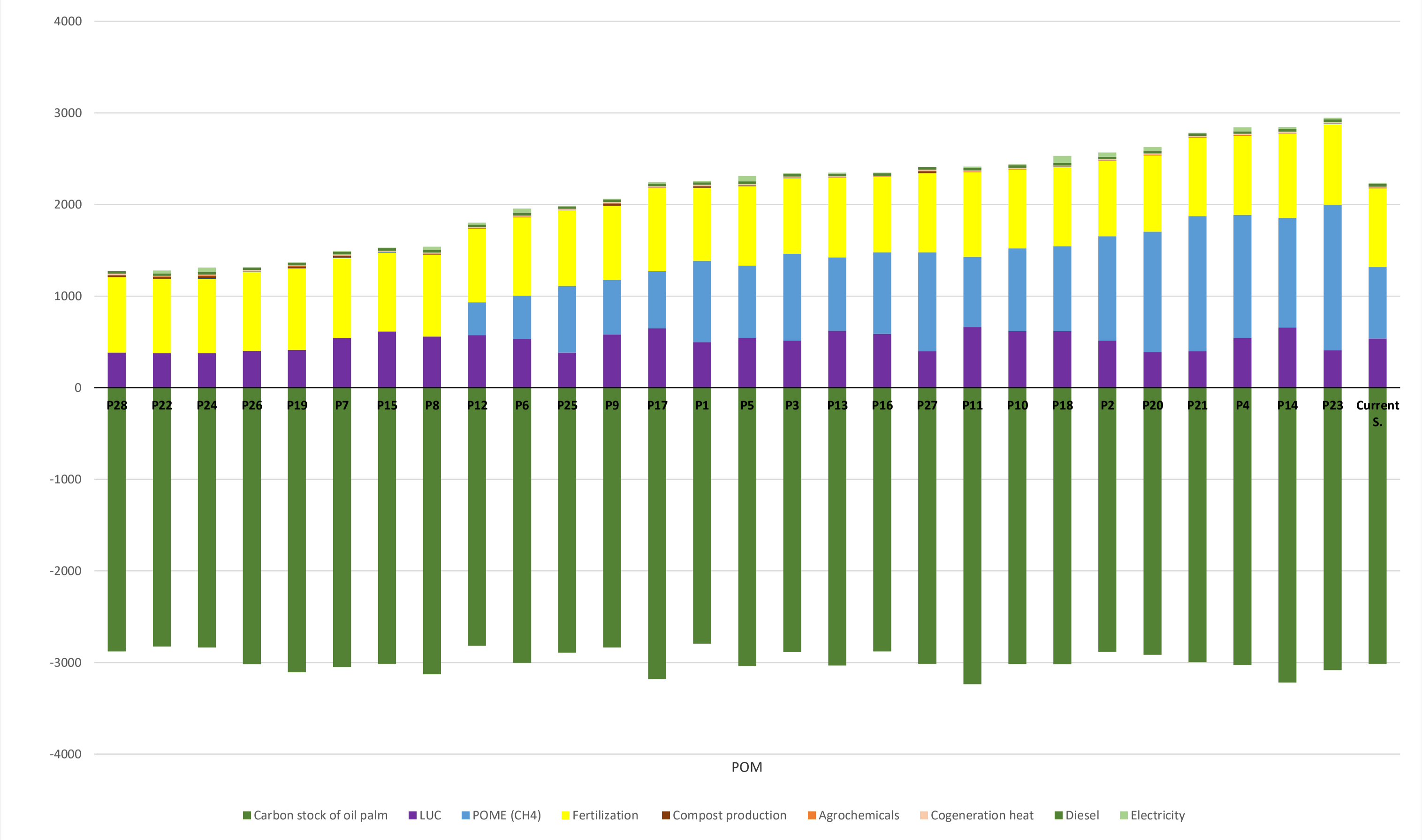

Figure 5. GHG balance in the current situation and emissions for each surveyed POM (Each mill is represented by the letter P and a number assigned from 1 to 28. The national average GHG emissions are shown in the "current situation" bar).

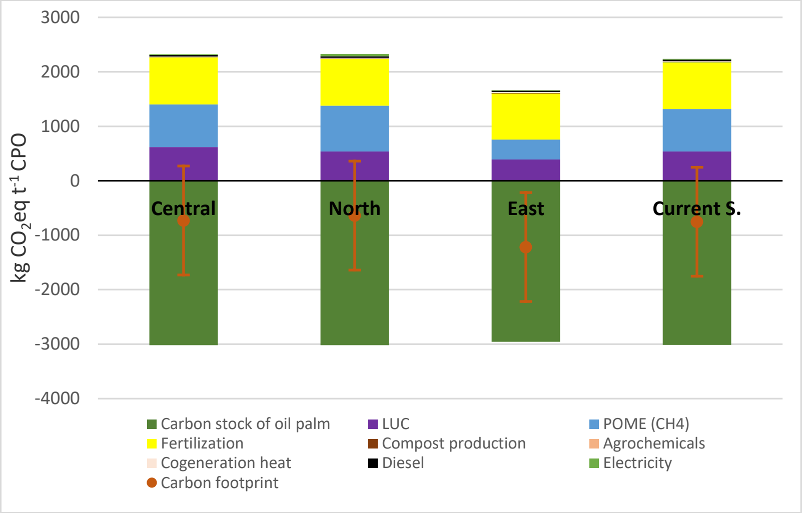

Figure 6. GHG emissions in each Colombian oil palm region (the orange bar represents the median, max., and min. carbon footprint data).

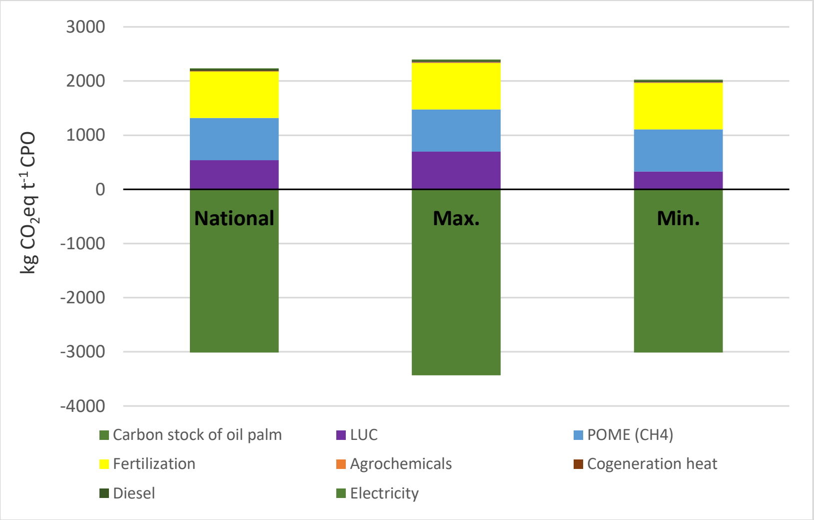

Figure 7. Impact of LUC on the GHG emissions in the production of CPO (sensitivity analysis).

3.3.2 GHG emissions in future scenarios

In both future scenarios A and B, it was assumed an increase in crop yield of about 3.5% compared to the *current situation*. Another improvement was the use of all biomass produced during the CPO extraction; also it included biogas capture and BD production. Figure 8 and Figure 9 show the overall mass and energy flows for both future scenarios A and B. The results are expressed per 1 t CPO. In *future scenario A*, the fiber, shells, and biogas were used to produce steam (4,095 kg t^{-1} CPO) and electricity (335 kWh t^{-1} CPO) to meet the demand of the whole system, with an electricity surplus of 115 kWh t^{-1} CPO, which can be sold to the national grid[31]. The EFBs were pre-treated through

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[31] More information about the conditions of sale of surplus electricity to the national grid can be found in the Colombian Resolution 030/2018 (CREG, 2018).

pressing and chopping and composted with the treated POME and the spent bleaching earth (SBE) from the CPO refining process. The compost was used in the field as an organic fertilizer, applied at a rate of up to 10% of that of chemical fertilization. In *future scenario B* (Figure 9), the pelletizing process requires a greater volume of steam to dry the biomass by 10%; and 86% of the biogas produced was used for producing steam in the boiler. As such, it is not possible to generate electricity with biogas. Therefore, in *future scenario B*, 27 kWh t^{-1} CPO of electricity must be purchased from the national grid in order to supply electricity for the process. In *future scenario B*, the volume of biogas required to generate electricity with a turbine (140 m^3 t^{-1} CPO) is greater than the volume of available biogas (118 m^3 t^{-1} CPO). Therefore, it is not possible to obtain an electricity surplus under the *future scenario B* conditions.

The GHG emissions along the CPO production chain in future scenarios A and B are shown in Table 6, along with GHG emissions from the *current situation*. Note that due to improvements made in the CPO production chain, total emissions in *future scenarios A and B* are lower than in the *current situation* as there are no CH_4 emissions and LUC emissions are reduced. Methane capture is a practice that reduces emissions immediately and generates an economic benefit to the POM since biogas can be used for power or heat generation, thus reducing the consumption of fossil fuels. Thereupon for future scenarios, crop fertilization will be the primary factor contributing to the emissions since oil palm crops have a high nutrient demand (Galindo and Romero, 2012). Fertilization emissions in *future scenario A* included compost application emissions (3.7 kg CO_2eq t^{-1} CPO), where each kilogram of compost replaced only 0.1 kg of chemical fertilizer. Notice that compost cannot be used as a total replacement or radical substitution for chemical fertilization because the release of nutrients from compost is a slow process and the oil palm crop requires high levels of available nutrients (Galindo and Romero, 2012).

When analyzing the system boundary until the biodiesel production plant, Table 7 shows that the carbon footprint of *future scenario A* is slightly greater (-679.6 kg CO_2eq t^{-1} BD), than the carbon footprint of *future scenario B* (-771.2 kg CO_2eq t^{-1} BD), mainly because fertilization emissions are higher in *scenario A*. For both future scenarios A and B, about 13% of emissions are due to LUC, about 68% is due to fertilization and agrochemicals, and about 11% corresponds to the process of refining-transesterification. When comparing these results with the results of the emissions in the study by Yáñez et al., 2011, which was a study that used information from the five BD producing companies in Colombia in 2010, it is observed that the greatest differences in the emissions come from the fertilization, POME (CH_4), diesel consumption and steam production. POME methane emissions are non-existent in *future scenarios A and B* of this study since the capture of biogas was assumed for power generation. In addition, emissions from diesel consumption are less in both future scenarios of this study due to it was not included the CPO transport because the mill and the BD plant are located in the same area.

3.3.3 Net energy ratio

Figure 10 shows a comparative analysis of NER for each scenario. In all cases, the crop stage had the highest fossil energy consumption (2.8 to 6.7 GJ t^{-1} BD). In the *current situation*, the NER is 2.2 MJ renewable MJ^{-1} fossil (Comparison1, C1 yellow line), where only fiber and shell are included as renewable energy sources. In contrast, the NER increases to 8.5 MJ renewable MJ^{-1} fossil (C8 yellow line) by adding CPO and all byproduct energy. In the *future scenarios A and B* (BD chain), the NER is greater than in the *current situation* (CPO chain), due to the increase in renewable energy from the primary products. For instance, in *future scenario A* for each unit of fossil energy required to produce BD and compost, 13.72 units of available renewable energy is obtained (C1 green line).

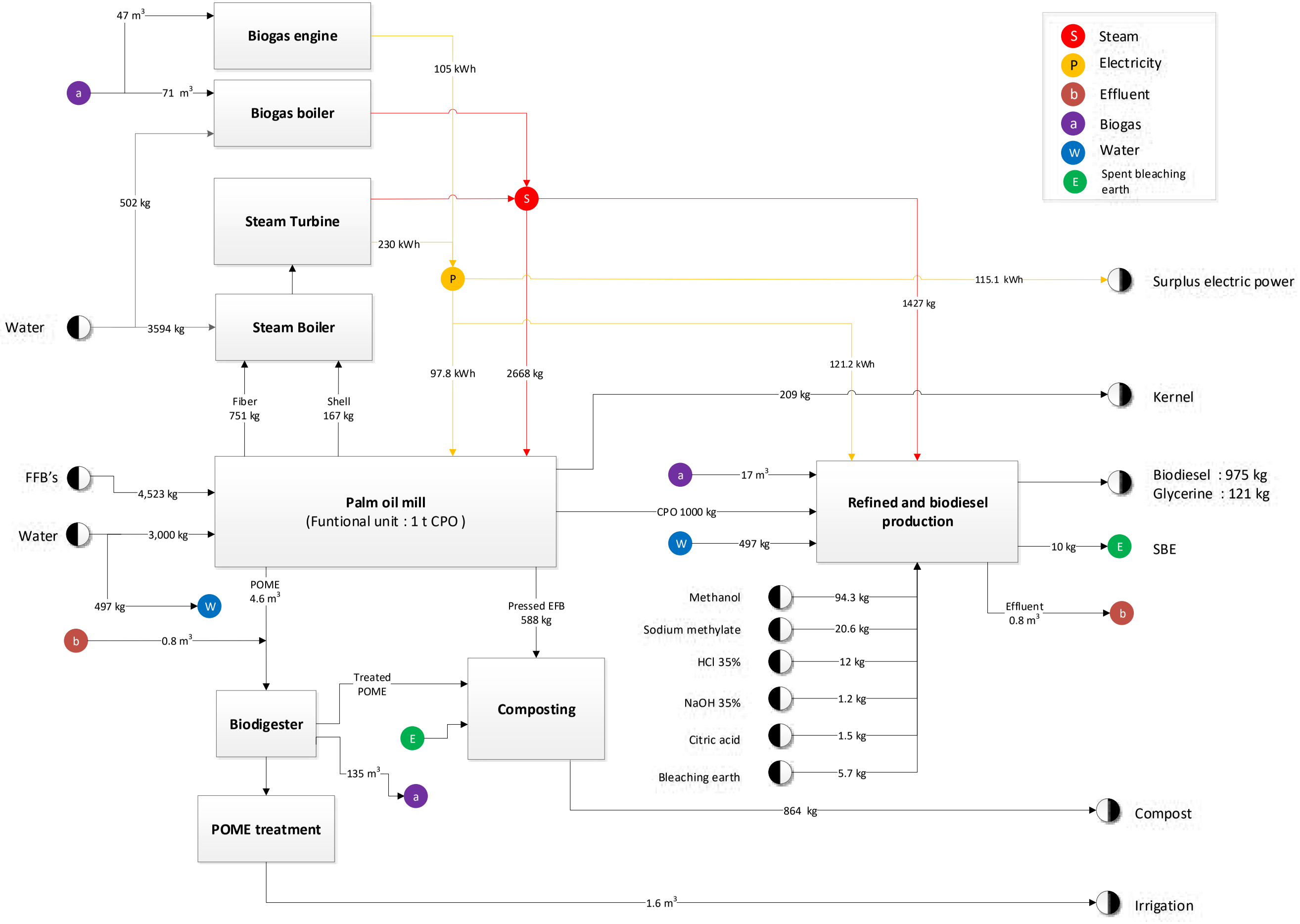

Figure 8. Mass and energy flows in future scenario A with compost production

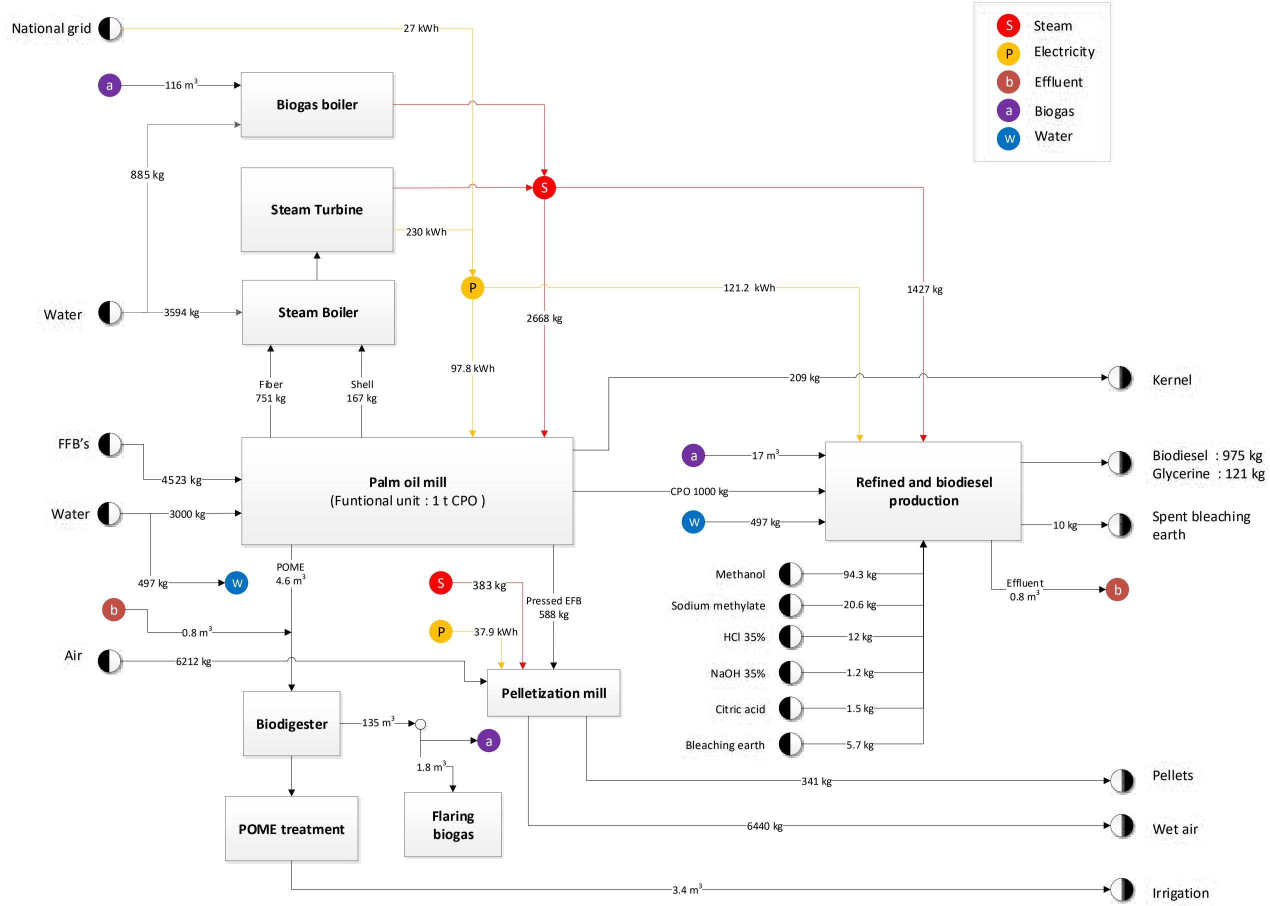

Figure 9. Mass and energy flows in future scenario B with pellet production.

Table 6. *Comparison in GHG emissions and carbon footprint in the CPO production chain for analyzed scenarios (kg $CO_2eq\ t^{-1}$ CPO).*

Source	Current situation	Scenario A	Scenario B
Carbon Stock			
Oil palm crop	-3,014.1	-1,852.3	-1,852.3
Emissions			
LUC	537.6	151.1	151.1
POME (CH_4)	778.7	0.0	0.0
Fertilizers	860.5	807.1	741.0
Compost production	0.0	3.7	0.0
Diesel	114.7	54.8	54.7
Cogeneration (power)	14.7	0.4	0.5
Cogeneration (heat)	9.1	7.6	7.6
Agrochemicals	6.3	4.3	4.3
Remnant processes	2.6	1.7	1.6
Total emissions	2,324.3	1,003.6	960.8
Balance			
Carbon footprint	-689.8	-821.7	-891.5

- Remnant processes contribute less than 1% to total GHG emissions.
- Carbon stock in oil palm crop includes the palm tree (fronds, trunk, and roots), cover vegetation, and associated organic matter. This value was estimated dividing by 30 years of plantation lifetime, and by the average yield of the plantation (t FFB ha^{-1}). The variation in the stock carbon of the oil palm crop between the *current situation* and the *future scenarios* is due to the crop yield assigned to each scenario (see Table 4).
- The emission/removal ratio in carbon stock in palm oil crop for the *current situation* is 0.74 (i.e. for each kg of CO_2 that is being absorbed; 0.74 kg CO_2 is emitted). For scenario A, it is 0.54 and for scenario B, it is 0.50, which means that less CO_2 is emitted in both future scenarios. Note that in scenario A, compost production generates emissions by its production and emissions by its application on the field.
- Fertilizer emissions in the future scenario will be lower than in the current situation; however, in scenario A, the emissions are greater than in scenario B due to the direct and indirect N_2O emissions caused by compost application.
- Compost emissions (CH_4 and N_2O) originate from the degradation of biomass.
- Diesel emissions correspond to the diesel consumption in FFB transport, tractors, and power plants in the mill.
- Cogeneration emissions are divided into power (electricity) and heat. Electricity emissions in the *current situation* correspond to the emissions of the four sources (diesel, national grid, cogeneration, and biogas), whereas electricity emissions in the future scenario account only for biogas and cogeneration (biomass). Biogenic CO_2 emissions of the biomass were not considered. Note that the difference in heat between the *current situation* and in the future scenario is due to increased steam consumption in the BD plant.
- Pellet production emissions are approximately 0.6%, which are included in the emissions by cogeneration (power and heat).

3.3.4 Economic performance assessment

3.3.4.1 Current situation

In the *current situation*, the CAPEX is estimated at 37.8 USD t^{-1} CPO (51% POM costs and 49% crop costs). The OPEX is estimated at 519.2 USD t^{-1} CPO (86% crop production costs and 14% POM costs) (Figure 11a). The processed FFB processed has an estimated value of 125 USD t^{-1} FFB. The NPV is estimated at 895 USD t^{-1} CPO and project profitability[32] shows 34% IRR. To quantify possible costs of breaches of environmental law, we assumed the mill was noncompliant with maximum permissible levels of contaminants in discharge, and the mill was closed for one week. As a result, the cost of that closure week is 3.6 USD t^{-1} CPO, which corresponds to the value of FFB processing in another mill. This could also imply other disadvantages, such as extra expenses for FFB transport over long distances and a reduction in the CPO selling cost with a poorer quality product below specifications (such as free fatty acid content, peroxides, and humidity). Figure 11a shows that CPO production costs are cheaper in *future scenarios A and B* than in the *current situation*. This due to the higher yield of the crop, the larger scale, and cheaper feedstock (FFB) at the mill. The estimated income of approximately 800 USD t^{-1} CPO is based on the expected sale of CPO (92%), power surplus (5%), and pellets (2%).

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[32] Note that companies must meet national, regional, and local regulations in order to operate within Colombian territory; including environmental regulations otherwise, those companies may face temporary or permanent closure.

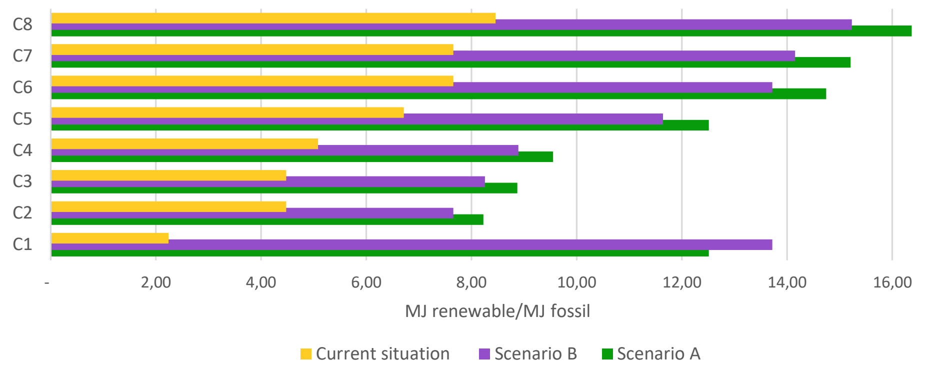
Table 7. *GHG balance in some studies of the Colombian palm oil sector.*

Process	**This study**			**(Yáñez et al., 2011)**	**(Henson et al., 2012)**	**(Garcia-Nunez et al., 2016)**	**(Rivera-Méndez et al., 2017)**
	Current situation	***Future scenario A***	***Future scenario B***				
Study area	28 POMs	Representative study case	Representative study case	Five BD plants	11 scenarios	Hypothetical POM	A specific plantation
Unit*	kg CO_2eq t^{-1} CPO			kg CO_2eq t^{-1} BD	kg CO_2eq t^{-1} CPO	kg CO_2eq t^{-1} FFB	kg CO_2eq t^{-1} FFB
Carbon Stock							
Palm oil crop	-3,014.1	-1883.9	-1883.9	-6,080.8	-894	-1071	-724
Emissions							
LUC	537.6	151.7	151.7	34.4	343	10.5	16
Fertilization	860.5	807.1	741.0	450.5	61	47.9	75
Agrochemicals	6.3	4.3	4.3	5.3	.	1.4	.
POME (CH_4)	778.7	0	0	945.6	179	361	.
Compost prod.	.	3.7	.	.	.	.	.
Steam produced	.	.	.	332.4	.	188	.
Diesel	114.7	54.8	54.7	468.6	255	17	17
Electricity	14.7	0.4	0.5	56.6	.	13	.
Cogeneration	9.1	7.6	7.6	.	.	76	.
Refining-BD ***	.	.	.	40.3	.	.	.
Remnant proc. **	2.6	1.7	1.6	374.2	.	0.04	10
Total emissions	2,237.7	1030.6	960.7	2707.9	838	633.3	118
Balance							
Carbon Footprint	-689.8	-721.7	-813.2	-3372.9	-56	-437.6	-606

* Unit: CPO = Crude Palm Oil; BD = Biodiesel; PO = Palm Oil; FFB = Fresh Fruit Bunches.

** Remnant processes contribute less than 1% to total GHG emissions.

*** Refining-BD process includes the inputs of the refining-transesterification process (methanol, sodium methylate, citric acid, hydrochloric acid, and SBE).



C1*	Shell + fiber (*current situation*)	BD + biogas + shell + fiber (*future scenario A*)	BD + biogas + shell + fiber + pellets (*future scenario B*)
C2	CPO	BD	
C3	CPO (no biogas in this situation)	BD + biogas	
C4	CPO + shell	BD + biogas + shell	
C5	CPO + shell + fiber	BD + biogas + shell + fiber **	
C6	CPO + shell + fiber + pellets	BD + biogas + shell + fiber + pellets ***	
C7	CPO + shell + fiber + pellets (no glycerin)	BD + biogas + shell + fiber + pellets + glycerin	
C8	CPO + shell + fiber + pellets + kernel	BD + biogas + shell + fiber + pellets + glycerin + kernel	

* C1 corresponds to NER values for the scenarios in the present study (*current situation*, *future scenario A*, and *future scenario B*). This value only includes products that function as renewable energy fuels.
** Future scenario A (pressed EFB are used for compost production and are not included as renewable energy)
*** *Future scenario B* (pellets are produced from pressed EFB).

Figure 10*. NER comparative analysis for the current situation and for future scenarios A and B.*

3.3.4.2 Future scenarios A and B

The CAPEX and OPEX are quite similar in both *future scenario A* and *future scenario B*. The CAPEX is estimated at approximately 49 USD t^{-1} BD (crop 32%, POM 29%, biogas/cogeneration 8%, BD plant 30%, and composting or pellets 1%). The OPEX is estimated at approximately 680 USD t^{-1} BD (crop 55%, POM 8%, biogas/cogeneration 2%, BD plant 34%, and composting or pellets approximately 1%). In *future scenarios A and B*, the NPV is estimated between 1,825 and 2,178 USD t^{-1}BD and the profitability of the project showed an IRR from 38 - 43%. An estimated income of approximately 1,075 USD t^{-1} BD is expected based on expected sales of BD (95%), power surplus sale (4%), and pellet sales (1%). Figure 11b shows that the BD production chain can be cheaper in *future scenarios A and B* across all stages of the production chain (crop, mill, and BD plant). Figure 11b also shows the prices of BD and diesel in Colombia. Since 2008, palm oil BD has been mixed with diesel for vehicular use, to reduce reliance on fossil fuels. However, due to the higher production costs of BD, the price of this biofuel is higher than the price of diesel. For instance, in Colombia, the historical price of BD has been around 30 USD GJ^{-1} while in 2017; the diesel price was approximately 10 USD GJ^{-1}. The diesel price per barrel was 54 USD/bbl and the average operating cost for oil production was 16.3 USD/bbl (extraction costs 47% and transportation costs 53%) (Hernandez et al., 2018b). The additional refining cost is estimated at approximately 30% more than crude oil. The oil price fluctuates over the medium and long term (van Vliet et al., 2009). Oil price projections could vary between 30USD and 119USD bbl^{-1} (2020-2030) (van Vliet et al., 2009) (Hernandez et al., 2018a). Considering the need to reduce environmental pollution, the national government has provided some incentives[33] for the production of BD, but in future, further assistance will be required to

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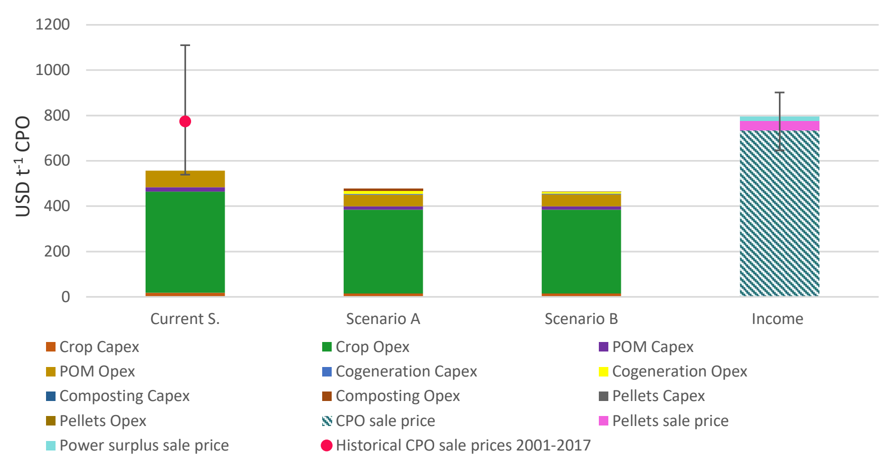
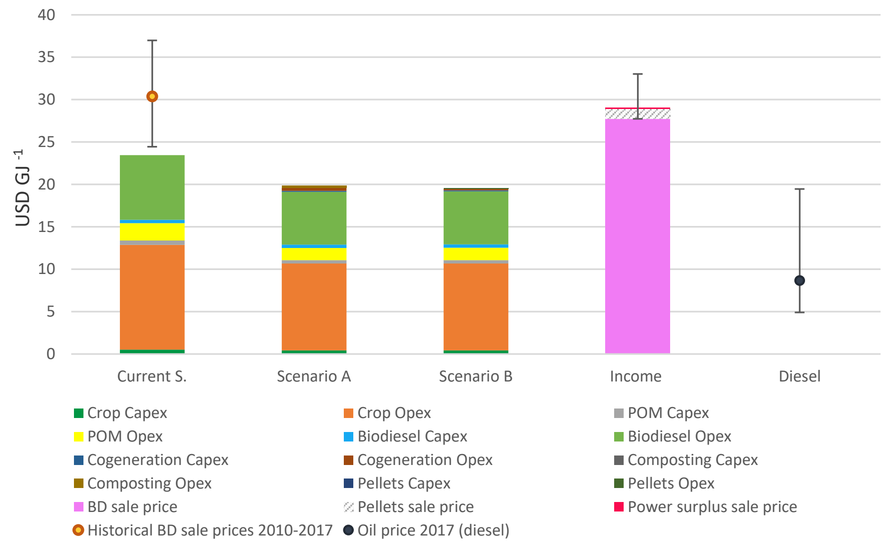
[33] Elimination of taxes for machinery and equipment purchase, reduction of income tax for companies in free zones, elimination of National Tax on gasoline and diesel (Law 939/2004). In addition, other benefits such as 1) reduction in logistics costs due to the availability of biofuel locally, compared to the costs of importing diesel. 2) Benefits associated with the costs avoided by the non-use of lubricity

reduce BD costs. Figure 12 shows the sensitivity of CPO production costs to scale applied to all scenarios. The crop yield increase (left) reduces the FFB production costs by 55% when proceeding from the *current situation* to *future scenarios*: the increase in the production scale at the POM (right) reduces the production costs by approximately 25% from the *current situation* to the *future scenarios*.



a) Costs analysis in the CPO production chain (CAPEX, OPEX, and Income)



b) Costs analysis in the BD production chain (CAPEX, OPEX, and Income)

Figure 11. *Cost comparison of the current situation and future scenarios A and B for CPO production (top graphic a) and biodiesel production (bottom graphic b).*

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improving additives for low and ultra-low sulfur diesel. 3) Benefits for the reduction of costs associated with premature mortality (mainly children and older adults) and morbidity (chronic respiratory diseases), generated by the reduction in toxicity of particulate matter emissions (PM10/PM2.5). 4) Benefits for the populations in the rural areas where the oil palm is cultivated (formal employment) (Torres, 2014).

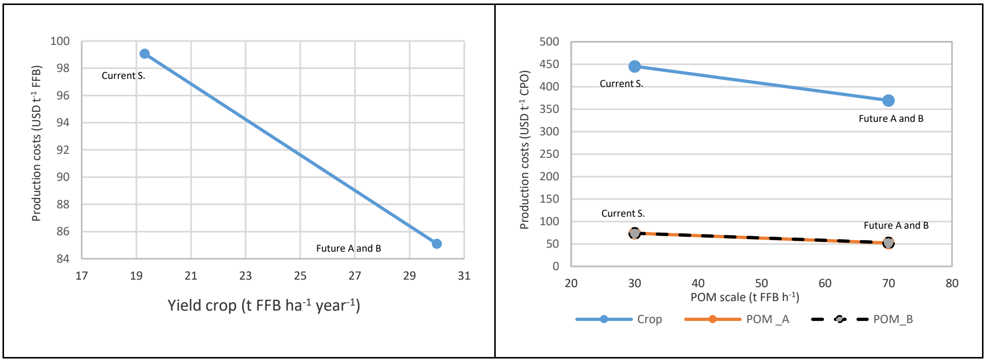

Figure 12. *Production costs in relation to crop yield (left graph) and to the scale of palm oil mill (right graph).*

3.4 Discussion

Table 7 shows a comparison of some recent **GHG balance** studies for Colombian palm oil, including the present study. Note that the GHG balance varies according to the assumptions made (e.g., data source, data representativeness, parameters included). Despite this, when comparing the carbon footprint reported for Colombia with the most recent analysis reported for Indonesia (0.7 and 26 t CO_2eq t^{-1} CPO (Lam et al., 2019)), the range of the carbon footprint for CPO production in Colombia remains much lower than for Indonesia. Worldwide in the CPO production, LUC, CH_4 emissions, and chemical fertilization have been the major contributors to GHG emissions (Wicke et al., 2008) (Yáñez et al., 2011) (Henson et al., 2012) (Castanheira et al., 2014) (Garcia-Nunez et al., 2016) (Lam et al., 2019).

As **LUC** strongly affects GHG balance (Wicke et al., 2008), the future expansion of palm oil crops in Colombia should be carried out in agricultural areas and livestock areas, with low carbon stock, to prevent deforestation and reduce LUC emissions (Castiblanco et al., 2013) (Pirker et al., 2016). Is highlighted that several studies have shown the deforestation of the forests in Colombia due to palm oil have been much lower than in other producing countries since the expansion has primarily occurred on pastures, herbaceous vegetation, and seasonal croplands (Henson et al., 2012) (Castiblanco et al., 2013) (Castanheira et al., 2014) (Furumo and Aide, 2017). Nevertheless, to prevent deforestation due to the agricultural expansion, strong guidelines, policies, and criteria are required to promote and regulate natural resources and efficient land use suitable for oil palm crops (Castanheira et al., 2014) (Woittiez, 2019) (Khasanah, 2019). Thereby, in the Land Suitability Map restrictions were considered to oil palm crops will not jeopardize natural areas or provision of ecosystem services (UPRA, 2016). A voluntary "Zero Deforestation" agreement was signed between the oil palm sector and the Colombian government, where the sector undertook to eliminate the deforestation footprint of its supply chain (MADS, 2019). In addition, the Colombian government for the proper use of the land is issuing several national laws and policies[34] (MADR, 2018). Besides, a strategy to move towards sustainable and low carbon growth, to protect biodiversity, improving environmental quality and governance, and achieving resilient growth that reduces vulnerability against the risks of natural disasters and climate change (DNP, 2018). On the other hand, since the impact of LUC emissions is linked to carbon stock changes, in Colombia, more precise data and mechanisms to monitor deforestation are required for emissions calculation. It is due to the huge diversity of the Colombian natural forests (from dry forest to tropical humid forest) (IDEAM et al., 2015), where the average carbon stock can vary between 48.1 t C ha^{-1} and 147.5 t C ha^{-1} (above-ground biomass) (Phillips et al., 2011). Then, applying good agricultural practices such as planning the

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[34] For instance, Land use policy (MADS, 2013). Definition of the agricultural frontier (MADR, 2018), among others.

crop location (soil quality, water) and increasing the crop yield will be important to reduce land-use emission (Gerssen-Gondelach et al., 2017), and also to reduce the CPO production costs (Beltrán et al., 2015) (Fontanilla, C;Mosquera, M; Ruiz, E; Beltrán, J; Guerrero, 2015) (Mosquera-Montoya et al., 2017).

CH_4 emissions from the POME treatment system in the *current situation* require great attention, since from the 28 POMs surveyed for this study, only eight mills reported CH_4 capture (biogas). Anaerobic POME treatment produces biogas, which is a mixture of gases where the major component is methane gas (50-70%) (Ohimain and Izah, 2017). Since the global warming potential of CH_4 is greater than that of CO_2 (IPCC, 2013), its capture and management as a renewable source of energy are essential. In the *current situation* of this study, the emissions from the POME treatment correspond to 35% of the total emissions of the CPO production, therefore the significant potential for reducing these emissions when capturing the biogas is considered in a future scenario. Even as analyzed in the *future scenario A and B*, the energy generation with biogas contributes to reducing the environmental impact and increasing the economic benefits of the sector. In addition to the biogas capture, the concept of zero waste at the exit of the POME lagoon system is emphasized to reduce the pollution of water sources (Espinosa et al., 2016), especially when in Colombia the maximum permissible parameters of water pollution are been stronger in recent years (MADS, 2015). For instance, the treated POME can be used for compost production or as irrigation water due to its high nutrient content (e.g., nitrogen, potassium, magnesium, and calcium) (Ramirez et al., 2011) (Ohimain and Izah, 2017). The Colombian government has encouraged the use of biomass and biogas for the generation of renewable energy, both to support the internal mill power demand and to the sell surplus electricity to the national grid, through tax incentives that promote the development and use of non-conventional energy sources (MADR, 2016) (Fedepalma, 2017b) (UPME, 2019). In a POM, an increase in biomass utilization efficiency can generate surplus energy for sale, as reported in *future scenario A*, where the use of biomass and biogas met the needs of the process and surplus energy was obtained.

Accordingly, the future CPO production chain must be focus on the emissions reduction to meet international sustainability standards, through the agro-industrial practices optimization that includes i) **increasing crop yield**, the Colombian oil palm sector has worked on the adoption of sustainable agricultural practices and technologies (Cooman, 2018). The aim of those practices is the achieving an increase in the national average yield from 16.2 t FFB ha^{-1} (Fedepalma, 2019) with a palm oil yield of 3.8 t CPO ha^{-1} (Cooman, 2018), to a crop yield around 24 t FFB ha^{-1} with a CPO production of 5 t ha^{-1} by 2023 (Cooman, 2018). However, in the future scenarios of this study, a crop yield of 30 t FFB ha^{-1}, which is equivalent to about 6.6 t CPO ha^{-1} (CPO extraction rate of 22.11%), is proposed. In this context, it is estimated that the oil palm sector of the country must make a great effort to increase the current yields. ii) **Reducing diesel consumption** is mainly focus on the FFB transport stage from the field to the mill, where the use of more efficient vehicles could contribute to reducing emissions. iii) **Adding value to biomass** would contribute to reducing negative environmental impacts and increasing the economic income of the palm sector. Since the biomass residues from the agricultural sector do not require additional land and are not useful for human consumption, it helps avoid deforestation and competition with food production (IEA Bioenergy, 2015). In Colombia, the palm oil sector has the potential for the production of lignocellulosic biomass of approximately one million tons (dry weight basis) with further increases expected but the future uses of biomass depend on its availability and cost (Ramirez et al., 2015). For example, the data collected during the fieldwork showed that most of the EFB did not have a specific use due mainly to the high costs of transport to the field. Consequently, EFBs are disposed of at landfills close to the mill, which has generated problems by the decomposition as leachate, and further CH_4 emissions. Therefore, compost or pellet production and cogeneration (heat and power) are some of the proposals of the future scenarios raised in this study.

The **NER analysis** in the BD production life cycle shows that the fossil energy consumed is lower than the renewable energy produced. The NER values reported in the literature for the BD chain in Brazil and Colombia are between 3.8 and 5.7 (Yáñez Angarita et al., 2009) (de Souza et al., 2010). However, a comparison of the energy balance including all products and byproducts shows that the potential NER value is higher. In an analysis of various biobased products from palm oil, the NER ranges from 17.7 to 22.9 (Garcia-Nunez et al., 2016). In our study, *future scenario B* has a higher NER than *future scenario A* (13.7 and 12.5, respectively). This is due to the production of pellets in *future scenario B* which increases the renewable energy produced, while the production of compost in *future scenario A* consumes a greater amount of fossil fuel. Thus, higher values of NER are observed when the use of biomass as renewable energy is increased (i.e. electricity, pellets, BD).

Regarding **economic performance**, the NPV and IRR are used as indicators of the economic viability of the palm oil sector. These vary according to the CPO market prices. The CAPEX depends on the mill scale and the machinery lifetime. The establishment of a palm oil plantation requires an initial investment and this crop requires a period of vegetative development prior to the beginning of the productive cycle (i.e. third year). Once the palm reaches its mature stage (i.e. year 7), FFB production tends to stabilize and there is income from FFB sales. The costs analysis is directly related to agricultural practices and industrial processing, and yield and costs for each stage in production chain must be optimized (greater profit margin) (Mosquera et al., 2014). Economic benefits and environmental benefits are realized from biomass use and improvements in production conditions, which increase yields in the supply chain. For instance, in the *current situation*, the crop yield was 19.3 t FFB ha^{-1} $year^{-1}$ and the mill processes 5,381 h $year^{-1}$, requiring the planting of 8,400 ha. However, by increasing the crop yields (30 t FFB ha^{-1} $year^{-1}$) and with a larger processing capacity and time process at the mill (i.e., 70 t FFB h^{-1} and 6,000 h $year^{-1}$), only 14,000 ha of oil palm will be required. This means greater FFB production per year with less land required.

3.5 Conclusions

This study evaluated the GHG emissions and the economic performance of the Colombian palm oil sector in the *current situation*. Besides, the analysis of two future scenarios, where the GHG emissions can be reduced through the application of good agricultural practices such as a) Reducing LUC impact through planting in suitable and available areas (cropland, pastureland); b) Reducing the use of chemical fertilizers with high carbon footprints (e.g., ammonium nitrate); c) Applying soil conditioners such as compost; d) Increasing crop yield and CPO yield per ha; e) Reducing diesel consumption, and f) Biogas capture. Also, using discharges from the POME system as water irrigation in nearby plantations, whenever possible. Improvements in the CPO production chain in both *future scenarios A and B* allow for a 55% decrease in GHG emissions compared to the *current situation*. In addition, the NER analysis in the BD production life cycle shown a renewable energy gain compared to the fossil energy input at the production system. Note the impact of LUC on total emissions depends not only on the change in land cover but also on the precise allocation of carbon stock values for the converted land cover (LUC mitigation through a sustainable crop yield increase is researched by the authors to an incoming paper).

For all scenarios, the crop operational costs represented the largest investment. However, it is expected that in the long-term scenarios, the total CAPEX and OPEX will decrease by approximately 20% in comparison to the *current situation*. The sale of surplus energy and pellets can contribute around 5 to 10% of the total income. Future economic evaluations could consider the fact that the investments are going to be staggered over time (e.g., first the planting phase, then the POM establishment and BD plant, etc.). Other scenarios could also be evaluated, such as those in which investors acquire the POM and buy all the FFB from suppliers, or those, which include income from the sale of carbon credits or products with sustainability labels supported by internationally recognized certification systems. The **key** point of this study is that there is significant potential for improvement in GHG balance in the BD production chain. In addition, the economic viability of the BD chain is improved through improving yield, the selection of low carbon stock lands, increased production scale, the production of biogas, pellets, and compost, and cogeneration. The second **key** point is that the sustainability of the palm oil sector requires enforcement of national policies on the use of available land and the prevention of deforestation.

Acknowledgments

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Appendix

A. LCI in the current situation

In this Appendix, additional information is provided on the input data used in this study, including data collected during the field visits to the 28 POMs.

A.1 Palm oil plantation

Table 4. LCI of the crop stage (Kg t^{-1} FFB).

General conditions	**Median**	**Max.**	**Min.**
Crop yield (t FFB ha^{-1} $year^{-1}$)	19.3	30	12
Annual precipitation (mm $year^{-1}$)	2,260	.	.
Chemical Fertilizer			
Ammonium nitrate	3.86	18.83	0.20
Calcium nitrate	0.01	0.01	0.01
Diammonium phosphate	0.01	0.01	0.01
Monoammonium phosphate	0.20	0.20	0.20
Ammonium sulfate	7.37	13.21	1.52
Urea	1.47	2.87	0.08
P_2O_5	1.08	10.49	0.08
K_2O	10.87	22.28	0.45
CaO	2.00	9.63	0.07
MgO	2.40	25.50	0.32
B	0.05	0.40	0.00
B_2O_3	0.40	0.65	0.02
S	0.48	8.72	0.02
Zn	0.04	0.10	0.00
Na	0.16	0.29	0.01
SiO_2	1.28	1.36	0.09
Agrochemicals			
Roundup	0.67	.	.
Monosodium methane arsenate	0.18	.	.
Fuels			
Diesel	4.65	16.75	1.82
Gasoline	0.04	0.58	0.01

A.2 POM stage

The primary input to the mill is the FFBs; to obtain1 t CPO, is necessary to process 4.68 t FFB. Table 5 shows the LCI for the POM stage. The electric power consumed in the mills came from four resources: the national grid (47%), cogeneration (30%), diesel generation (13%), and biogas generation (9%). The electricity emissions from the national grid were considered (86% hydroelectric power, 9.3% natural gas, 3.6% coal, and 0.9% biomass) (UPME, 2018).

Table 5. Life cycle inventory of the POM stage.

Inventory	**Unit**	**Median**	**Max.**	**Min.**
FFB processed	kg t^{-1} CPO	4683.26	5205.76	4341.81
Palm Kernel recovery rate	kg t^{-1} CPO	214.56	288.73	117.99
Diesel for FFB transport	gal t^{-1} CPO	2.63	2.63	2.63
Electricity requirement by POM	kWh t^{-1} CPO	102.81	188.78	35.27
Water requirement for FFB processing	m^3 t^{-1} CPO	2.59	12.26	0.14
Water requirement for the steam boiler	m^3 t^{-1} CPO	2.45	5.13	1.43

Diesel requirement to produce electricity	gal t^{-1} CPO	0.36	4.03	0.02
Diesel requirement to use in other activities	gal t^{-1} CPO	0.13	1.30	0
EFB generated	kg t^{-1} CPO	1050.79	1345.62	749.76
Fiber generated	kg t^{-1} CPO	613.88	786.09	456.92
Fiber to fuel the boiler	kg t^{-1} CPO	476.42	720.75	235.03
Palm kernel Shell generated	kg t^{-1} CPO	221.72	381.38	147.92
Shell to fuel the boiler	kg t^{-1} CPO	214.82	315.25	0
POME	m^3 t^{-1} CPO	3.34	13.50	0.85
Treated POME	m^3 t^{-1} CPO	1.93	4.59	0.49
COD from POME	kg t^{-1} CPO	192.34	1236.12	78.00
COD from treated POME	kg t^{-1} CPO	2.83	14.36	0.42
COD removed	kg t^{-1} CPO	188.61	1231.32	76.58

Figure 4 shows electricity consumption nationwide in the POMs, highlighting the eastern region, whose dependence on the national grid is lower than in other palm oil regions, because in this region there are areas that are non-interconnected to the national grid. In addition, in the central region, no mill reported power generation from biogas.

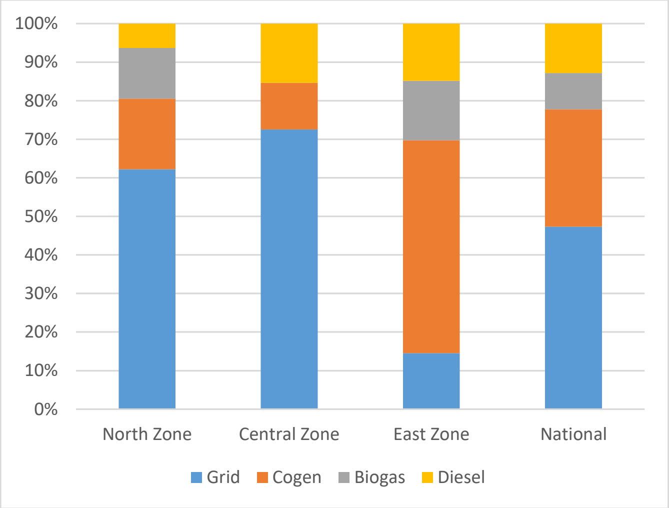

Figure 4. Electricity consumption per generation source nationwide and per palm oil region.

B. LCI in future scenarios A and B

In the future scenarios, the production of BD, compost, pellets, cogeneration, and biogas capture was included in the system boundaries as improvements in the use of biomass, to reduce GHG emissions, and to provide additional economic benefits. All the fiber and shells produced in the mill were used as fuel for steam and electricity production. Although the use of biomass for compost in the plantation for nutrient recycling was evaluated, compost cannot be used as a total replacement or a drastic substitution for chemical fertilization because palm oil crops have high nutrient demands. Also, the release of nutrients from compost is slow, and compost can be used as a supplement to fertilization, or as an organic amendment that improves soil properties to retain more nutrients (Galindo and Romero, 2012). The transportation of bio-based products to the wholesale distributor, user, and final destination was not considered in this study. Biogenic CO_2 emissions were not taken into account in the GHG balance.

B.1 Compost production in future scenario A

In *future scenario A*, the pressed EFB and treated POME were used in the production process (3.2 m^3 POME t^{-1} EFB). We assumed there was no leachate during the composting process, a treated POME density of 1,000 kg m^{-3} ; the pressed EFB moisture of 49.2%, and composition of N 0.9%; P_2O_5 0.3%; K_2O 2.0%; CaO 0.4%; MgO 0.3%. The compost moisture was assumed to be 32.5%, with composition of N 1.77%; P_2O_5 1.20%; K_2O 2.30%; CaO 3.60%; MgO 1.40%. The compost sales price was not considered in the economic analysis, because the compost was applied to the same plantation.

B.2 Pellet production in future scenario B

In *future scenario B*, the pressed EFB was used for pellet production. There is a need for biomass storage at the POM during periods of low FFB harvest. However, biomass storage is challenging since the biomass has a moisture content higher than 30% (by weight) which causes organic degradation problems during storage (Stichnothe et al., 2016). To reduce the moisture, EFBs must undergo additional drying treatment (up to 10% moisture) and additional chopping (to less than 2 mm).

Chapter 4

GHG balance of agricultural intensification & bioenergy production in the Orinoquia region, Colombia

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Abstract

Energy crop expansion can increase land demand and generate displacement of food crops, which impacts greenhouse gas (GHG) emissions mainly through land-use change (LUC). Increased agricultural productivity could compensate for this. Our study aims to evaluate the regional combined GHG emissions of increasing agricultural yields for food crop and beef production and using the generated surplus land for biomass production to replace fossil fuels in the Orinoquia region of Colombia until 2030. The results show that surplus land for biomass production is obtained only when strong measures are applied to increase agricultural productivity. In the medium and high scenario, a land surplus of 0.6 and 2.4 Mha, respectively, could be generated. Such intensification results in up to 83% emission reduction in Orinoquia's agricultural sector, largely coming from increasing productivity of cattle production and improving degraded pastures. Biofuel potential from the surplus land is projected at 36 to 368 PJ per year, with a low risk of causing indirect LUC, and results in GHG emission reductions of more than 100% compared to its fossil fuel equivalent. An integrated perspective of the agricultural land use enables sustainable production of both food and bioenergy.

4.1 Introduction

Based on the need to reduce fossil fuel consumption and GHG emissions, bioenergy production has increased in the past decades, and it is projected to continue to grow (OECD-FAO, 2019). However, expansion of energy crop production could incur increased land demand, and thereby increase greenhouse gas (GHG) emissions due to direct and indirect land-use change ((I)LUC) (European Parliament, 2018). To minimize these effects, the sustainability criteria of the Renewable Energy Directive (RED II) require low-ILUC risk-biofuels and minimum GHG emission savings compared to the fossil fuel equivalent (European Parliament, 2018). Biofuels are considered to have a low-ILUC-risk, when energy crops are cultivated on surplus land that can be made available due to the implementation of measures to further increase yields of agricultural production compared to a business-as-usual scenario (European Commission, 2019). Producing energy crops at surplus land obtained through agricultural intensification reduces the risk of LUC and (I)LUC related GHG emissions (de Souza et al., 2019; Gerssen-Gondelach, Wicke, & Faaij, 2017; Jimenez & Faaij, 2012).

Colombia has been promoting the development of a sustainable biomass and bioenergy sector in the last decade (DNP & Enersinc, 2017). The efficient use of agricultural land has been an important objective of development, as current agricultural land use has low productivity and there is a potential risk the agricultural sector continues to develop in an inefficient way (CIAT & CRECE, 2018) (DNP, 2018) (Rodríguez Borray, Bautista Cubillos, & Comps., 2019). The Ministry of Agriculture and Rural Development recently delimited the agricultural frontier, indicating which land could potentially be used for agricultural activities and aiming to avoid the expansion of agricultural production in protected areas (MADR, 2018b). The Orinoquia region is one of the regions with the largest area available within the agricultural frontier (UPRA, 2018a). Currently, 55% of the area in the region is used for extensive cattle ranching, 5% for agricultural production, 1.3% of the area is water surface, 0.04% for forestry production, and the remaining 38.6% for other uses (e.g., oil extraction, urban areas, natural vegetation, etc.) (CIAT & CORMACARENA, 2017). Theoretically, the area within the agricultural frontier could be used for agricultural expansion to accommodate the projected increase in demand for agricultural products and for energy crop production, However, given that the land within this agricultural frontier consists mainly of natural vegetation, this is highly likely to result in high LUC-related GHG emission and other negative environmental impacts. To increase agricultural production sustainably and produce low-ILUC-risk energy crops, agricultural intensification is required.

Considering the current inefficient agricultural land use in the region, there is a significant potential to intensify agricultural production. Especially, the intensification of the extensive cattle production system could lead to lower land requirements. The available land could be used for other uses such as for energy crops (FAO, 2013) (Fedegan, 2018a) (Lerner, Zuluaga, Chará, Etter, & Searchinger, 2017) (Younis, Trujillo, Benders, & Faaij, 2020). However, agricultural intensification could also result in additional GHG emissions depending on inputs and management practices (Gerssen-Gondelach et al., 2017). Several studies on land use change in Orinoquia region have reported changes in carbon stocks (C-stocks) due to land conversion (Castanheira, Acevedo, & Freire, 2014) (Quezada, Etter, Ghazoul, Buttler, & Guillaume, 2019) (Silva-Parra, 2018). Moreover, some studies reported GHG emissions from agricultural production (Castanheira et al., 2014) (Peñuela, Ardila, Rincón, & Cammaert, 2019) (Ramirez-Contreras, Munar-Florez, Garcia-Nuñez, Mosquera-Montoya, & Faaij, 2020). However, the joint GHG emission impacts of i) increasing agricultural yields of food crop and beef production, and ii) biofuel production on surplus land generated through intensification is not known.

This study aims to evaluate the GHG balance of different levels of agricultural intensification and using the generated surplus land for biomass production to replace fossil fuels in the Orinoquia region of Colombia. The analysis focuses on developments until 2030. The GHG balance is evaluated for three agricultural intensification scenarios and a reference scenario, in combination with three bioenergy production routes: ethanol from sugarcane, biodiesel from oil palm, and electricity production from acacia.

4.2 Materials and Methods

4.2.1 Study Area

The Orinoquia region of Colombia includes the departments of Arauca, Casanare, Meta, and Vichada. It covers about 25.4 Mha (DANE, 2016b) of which about 9.9 Mha (i.e., 39%) are no-go areas for agricultural activities (i.e., natural forest, national parks, indigenous areas, archaeological heritage areas, etc.) (UPRA, 2018a). Approximately 15.5 Mha (i.e., 61%) is within the agricultural frontier of which 7 Mha is currently used for agricultural production (i.e., 10% cropland and 90% pastureland) (Agronet, 2019) and 8.5 Mha, which consists of flooded savannas and shrubland, is considered to be available for agricultural production (Agronet, 2019). Extensive cattle grazing (0.6 Animal Unit ha-1, where one animal unit is equivalent to 450 kg of average animal-live-weight (Fedegan, 2018a)) occupies around 6.2 Mha (MADR, 2018a) and is one of the key economic activities of the region (CIAT & CORMACARENA, 2017) (Fedegan, 2018a) (Ramírez-Restrepo, Vera, & Rao, 2019). About 0.6 Mha is currently used as cropland, where the most dominant crops in terms of cultivated area are oil palm (33%), rice (32%), plantain (14%), corn (10%), soybean (7%), and cassava (3%) (Agronet, 2019).

The Orinoquia region includes five subregions, i.e., Andes mountains, foothills, flooded plains, highplain, and an ecosystem transition region (Figure 1). The ecosystem transition region is the transition area between the savannas and the Amazon. Both the ecosystem transition and the Andes Mountain region are part of the 9.9 Mha of no-go area for agriculture activities. The flooded plain, foothills, and highplain subregions are within the agricultural frontier and are therefore included in this study. Despite the flooded plain remain flooded most of the year ($^{+}/_{-}$8 months) (Peñuela et al., 2019) (Rincón et al., 2014), this area has been used for small-scale extensive cattle production for decades (Peñuela et al., 2019). According to the Rural Agricultural Planning Unit of Colombia (Unidad de Planeación Rural Agropecuaria de Colombia, UPRA), this area has low suitability for crop production but has the potential to continue cattle production (UPRA, 2018b) in small-scale (Peñuela et al., 2019). The foothills and the high plains subregions hereinafter called “foothills–highplain area" are currently used mostly for large-scale extensive cattle production (Rodríguez Borray et al., 2019). This area has the highest potential to increase cattle productivity and generate potential suitable surplus land (CIAT & CORMACARENA, 2017). The land distribution (in Mha) and land suitability for crop and cattle production of the three subregions are reported in Table A6 in the Appendix.

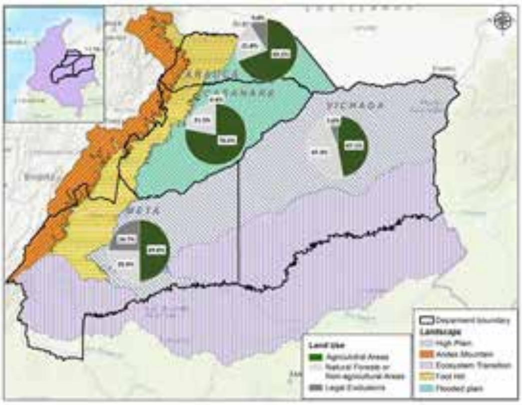


Figure 1. Location of the subregions and administrative departments of the Orinoquia region of Colombia. The pie charts show the composition of current land use in each department. Based on

information from (Rincón Castillo & Jaramillo, 2010) (Rincón et al., 2014) (UPRA, 2018a) (UPRA, 2018b).

4.2.2 General Approach

The net GHG balance of the Orinoquia region for 2030 is calculated considering i) agricultural intensification of food crop and beef production and ii) bioenergy from energy crops produced on the generated surplus land. We first determine agricultural production for 2030 (Section 2.3). Since most of the crops produced in the region are destined for human consumption, they are referred to as food crops in this study. Moreover, since most of the region's cattle production is dedicated to beef production, only beef production is included in this study. Next, we assess how agricultural productivity may develop until 2030 and calculate the resulting surplus (or shortage) of land (Section 2.4). Our analysis is conducted for four scenarios; besides a reference scenario, which assumes a business-as-usual development in agricultural intensification, three agricultural intensification scenarios are included (low, medium, high). We then determine GHG emissions for agricultural production and intensification (Section 2.5), for bioenergy supply chains and their reference fossil fuel chains (Section 2.6) and land use change (Section 2.7). Three biomass production routes (i.e., sugarcane bioethanol, palm oil biodiesel, and acacia wood for bioelectricity) are considered, assuming production only takes place on surplus land. Note that each energy crop is analyzed individually, which means, each energy crop is planted on 100% of the land released in each scenario (i.e., only oil palm, or only sugarcane, or only acacia is planted on surplus land by scenario). We do not consider planting the three energy crops at the same time in an area. By combining the GHG emissions of agricultural intensification, bioenergy production, and LUC, the overall GHG balance for the region is estimated for each scenario and each energy crop. Figure 2 presents an overview of the main steps of our approach.

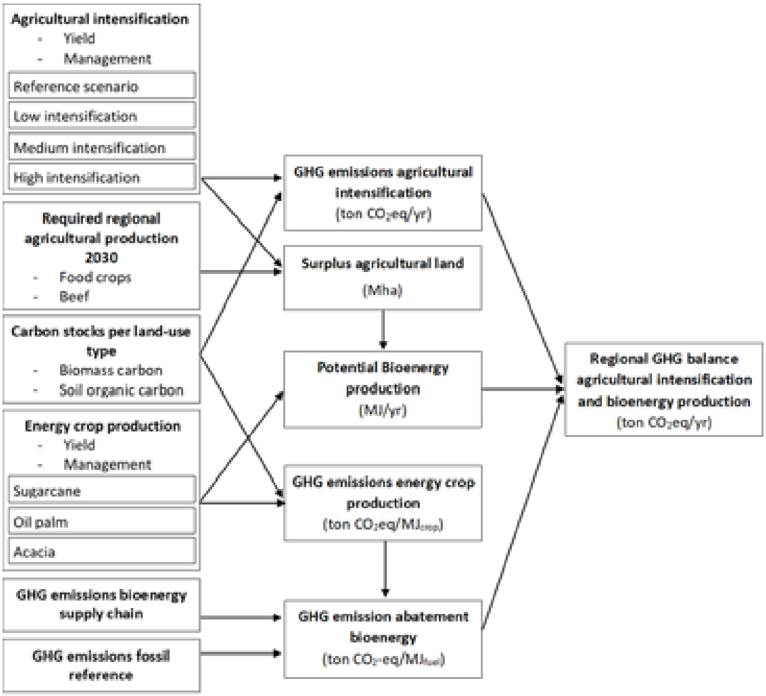


Figure 2. Methodological approach to assess the GHG balance of agricultural intensification and using the generated surplus land for bioenergy production to replace fossil fuels.

4.2.3 Agricultural Production in 2030

Food production in the Orinoquia region in 2030 is calculated according to Equation (1). Food production is estimated at national level, multiplying the estimated national population in 2030 with the per capita consumption, the self-sufficiently ratio (SSR) and food losses of each food product. National food production is then multiplied by the contribution of the Orinoquia region to the national production of each food product. The per capita consumption of food products in Colombia is expected to increase towards 2030 (MADR, 2016) (OECD-FAO, 2019). In line with the studies of MADR, (2016) and Younis et al, (2020), the SSR, food losses, and the relative contribution of Orinoquia region to national food production are assumed to remain stable to 2030. The land demand projection for agriculture in 2030 is based on the amount of land in use in 2018 (crops and cattle). For input data, see Table A1 in the Appendix A.

$$FoodPro_i = Pop * Con_i * SSR_i * P_{i.orq} * (100\% + Loss_i) \qquad \textit{Equation 1}$$

Where: *FoodPro$_i$* = Orinoquia food production (t yr^{-1}); *i* = Food product (rice, corn, soybean, cassava, plantain, palm oil, and beef); *Pop* = National population; *Con$_i$* = Per capital consumption for food product *i* (kg $person^{-1}$ yr^{-1}); *SSR$_i$* = Self-sufficiently ratio of food product *i* (%); *$P_{i.orq}$* = Orinoquia contribution to national production per each food product *i* (%); *Loss$_i$* = Food losses in the supply chain for food product *i* (%).

After calculating the production per food product for 2030, we calculate the land required for food production in 2030 for each scenario by dividing the production by the yields related to each scenario Equation (2).

$$LandD_i = FoodPro_i / Yield_{i\,Scenario} \qquad \textit{Equation 2}$$

Where: *LandD$_i$* = Land demand for food production (ha); *FoodPro$_i$* = Orinoquia food production (t yr^{-1}); *$Yield_{iscenario}$* = Yield of food product *i* for each scenario (*reference*, *low*, *medium*, and *high*) (t ha^{-1} yr^{-1}).

4.2.4 Agricultural Intensification (Food Crops and Cattle)

Increasing agricultural productivity in the region could generate surplus land if the increase in productivity surpasses the increase in demand for agricultural products. Figure 3 illustrates how surplus land is determined, i.e., the difference between current land demand and future land demand that is projected according to different levels of agricultural intensification (see Table 1). The intensification scenarios assume improved agricultural practices such as the efficient use of fertilizers and the reduction of fossil fuel consumption. Before describing the key characteristics of improved agricultural practices and resulting yields below, we first summarize the scenarios here; additional information on the scenarios can be found in Appendix B. The reference scenario follows the conventional agricultural conditions (i.e., inefficient practices in fertilizer application and soil management). For the low intensification scenario, conventional agricultural practices are assumed, with an increase in crop yield based on some improvement in fertilizer application. In the medium intensification scenario, improvement of some agricultural practices is assumed such as crop fertilization and improved cattle management (cattle are fed with improved grasses and forage sorghum). For the high intensification scenario, sustainable intensification is assumed, with fertilizer application in accordance with soil requirements, soil improvements, and improved cattle feed quality (see Appendix B).

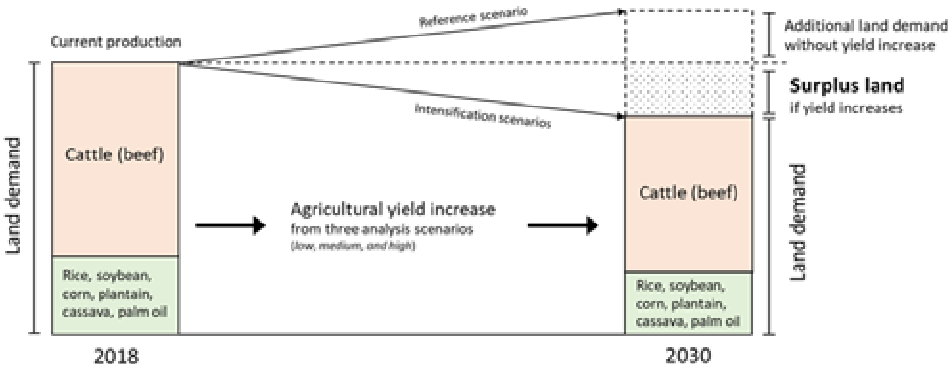


Figure 3. Projected surplus land in 2030 due to intensification of beef and food crop production.

4.2.4.1 Food Crop Production

According to UPRA (2019), current fertilizer use is inadequate in Colombia since the application is not carried out based on soil analysis or plant nutrient requirements. This can result in deficits or excess of fertilizers and affects crop yields (UPRA, 2019). In this study, the fertilizer inputs per scenario, to achieve the crop nutrition requirements, consider the three main nutrients Nitrogen (N), Phosphorus (P), and Potassium (K). The amount of nutrients (kg ha^{-1}) applied to each crop is based on literature and is related to the yield (see Table A2 in the Appendix). Another important factor in agricultural yield intensification is crop mechanization (Gerssen-Gondelach et al., 2017). Agricultural mechanization in Colombia is used mostly for soil preparation and harvesting, while the other tasks can also be carried out manually (UPRA, 2019). Rice is the crop that uses the most machines/equipment in Colombia (UPRA, 2019). In the Orinoquia region, rice is grown in rainfed conditions (dry rice), which means this crop receives water mainly from rainwater. Therefore, it does not require mechanization linked to irrigation (UPRA, 2019). Although currently mechanization is used in agriculture, there is not enough available historical data about fossil fuel consumption related to each crop in Colombia. Therefore, diesel usage in the reference scenario is based on literature as shown in Table A2 in the Appendix. For the intensification scenarios, diesel consumption was assumed to reduce by 10% in the high scenario compared to the reference scenario, based on the study by Brinkman et al. (2018) (see Table A2 in the Appendix).

To establish the crop yield levels for each scenario, data analysis of agricultural yields for the period 2012-2018 for the Orinoquia region was conducted. The yield levels in the reference scenario are set at the 50th percentile of the reported yield levels in Orinoquia region in the period 2012-2018. The low scenario is set at 65th percentile, the medium scenario is set at 80th percentile, and the high scenario is set at the 95th percentile of the yield levels of the Orinoquia region in the period 2012-2018. Thus, for example, the rice crop yield is 4.97 t ha^{-1} yr^{-1} for the reference scenario and for the intensification scenarios, crop yields are 5.06; 5.26; and 5.96 t ha^{-1} yr^{-1} for the low, medium, and high scenarios, respectively. Projected yields for all food crops are shown in Table 1.

4.2.4.2 Beef Production

To increase cattle productivity, the production system can be intensified by several improvements such as fertilizing pastures, improved grasses, a better quality of animal feed, and pasture rotation (Chará et al., 2019) (DANE, 2016a) (Etter & Zuluaga, 2017) (Peñuela et al., 2019) (Tapasco, Lecoq, Ruden, Rivas, & Ortiz, 2019). The current cattle production in the region is carried out in an extensive system. Considering that in this system i) the pastures do not receive fertilization at any time of their lifetime, and ii) the soil of the region is low in nutrients (Rincon Castillo, Baquero, & Florez, 2012), we assume that the land from current cattle production is degraded. Since all future scenarios include cattle production on the current degraded land, we assume that in all future scenarios the land used for cattle is degraded. However, as better practices are applied to increase productivity, the increase in beef yield includes the improvement of cattle production systems with the use of improved (fertilized) pastures and silvopastoral systems as described as follow.

For the reference and low scenario, the current extensive production system of the foothill-high plain area is assumed, in which animal feed is based on pastures with low nutrient levels (e.g., *Trachypogon vestitus*) (CIAT, 2001) (Rincon Castillo et al., 2012) (Rodríguez Borray et al., 2019). For the medium and high scenarios, it is assumed the cattle feed quality is improved (see Appendix B), using improved grassland (e.g., *Brachiaria decumbens*) and forage sorghum for the medium scenario (Rincón Castillo & Jaramillo, 2010). While a mix of improved grassland (e.g., *Brachiaria decumbens*), fodder plants (e.g., leguminous herbs, and shrubs/trees), and forage sorghum improve the quality of the animal feed in the high scenario (it has been considered that for sustainable development of cattle production, the use of a silvopastoral grazing system is proper (Chará et al., 2019)). It was considered that the sorghum forage needs to be cultivated within the land used for cattle production. This land use is included in the total GHG emissions for cattle production as feed emissions. The characteristics of the production systems for the reference and intensification scenarios are described in the Appendix B. The projected increases in cattle productivity for the intensification scenarios follow the three levels of projected productivity increases of the Colombian livestock strategic plan of the National Federation of Breeders (Fedegan, 2006, 2018a). We consider these projected increases in cattle productivity realistic given the large range in current productivity, wherein some traditional farms an animal density of 1.5-1.8 heads per hectare is achieved. while in farms with improved systems animal densities of 3-4 heads per hectare are realized (Fedegan, 2020). The resulting yields are reported in Table 1.

Table 1. Yield levels and cattle densities for the reference and agricultural intensification scenarios.

Characteristics		**Scenarios 2030**				**Data sources**
		Reference	Low	Medium	High	
Yield food crops [a] (t ha^{-1} yr^{-1})	Rice	4.97	5.06	5.26	5.96	(Agronet, 2019); (Fedepalma, 2019b); (DANE, 2019a)
	Corn	5.50	6.00	6.00	7.00	
	Oil palm (crude palm oil)	2.41	2.62	2.96	3.30	
	Plantain	13.00	16.00	18.00	22.45	
	Soybean	2.50	2.53	2.80	3.00	
	Cassava	14.00	15.00	18.00	20.74	
Livestock productivity (AU ha^{-1}) [b]	Cattle	0.6	1.0	1.5	2.0	(Fedegan, 2006); (Fedegan, 2018a)

[a] Food crop yields increase are based on historical data analysis of agricultural production for the period 2012-2018 for the whole Orinoquia region.
- *Reference* scenario: 50th percentile yield level
- *Low* scenario: 65th percentile yield level
- *Medium* scenario: 80th percentile yield level
- *High* scenario: 95th percentile yield level

[b] AU = animal unit. One AU is equivalent to 450 kg of average animal-live-weight (Fedegan, 2018b).

4.2.5 GHG Emission Associated with Agricultural Production

The GHG emissions of agricultural production were calculated for each scenario, taking a system boundary of cradle-to-farm gate. The emissions for all crop systems are expressed as kg CO_2eq t^{-1} of product, which corresponds to tons of rice, tons of corn, tons of soybean, tons of plantain, tons of cassava, and tons of oil palm-fresh fruit bunches. For beef production, the emissions are expressed as kg CO_2eq t^{-1} beef. The emissions include LUC-related emissions (see section 2.7) and the emissions related to (annual and perennial) crop cultivation and beef production. The GHG emissions related to crop production include emissions of fertilizer production, fertilizer application, and diesel usage. In addition, since one of the annual crops is rice, methane (CH_4) emissions from rice production are included following the Equation (A3) and Equation (A4) in the Appendix B. The fertilizer application rate is related to the yield and the nutrition requirements of each crop, see Table A2 in the Appendix B. For example, it was assumed that in a sustainable scenario like our high scenario, the fertilizer is applied according to the soil requirements. Furthermore, to improve the fertilization of crops, we assumed an increase in the efficiency of the use of nitrogen fertilizers that includes both the use of good agricultural practices and the use of slow-release nitrogen fertilizers (Appendix B). Emissions from fertilization include fertilizer production and direct/indirect N_2O emissions of fertilizer application. For the diesel usage, we assumed the fossil fuel use by machinery goes down with higher agricultural yields, due to higher efficiency of the agricultural operations per ton of output. Diesel usage per crop per scenario, emission factors of fertilizers, and fertilizer application are included in Table A2 and Table A3 in the Appendix B.

The GHG emissions from beef production includes emissions from feed production (CO_2 and direct/indirect N_2O; these emissions are calculated as for food crops), enteric fermentation (CH_4), and manure management (CH_4 and direct/indirect N_2O). Emissions were calculated following IPCC 2019 Refinement guidelines (i.e., equations: 10.21; 10.22; 10.30; 11.1; and 11.5) (IPCC, 2019). Note that for all scenarios in this study, it is estimated that all cattle production is run on a grazing system. Therefore, following the IPCC 2019 method, it corresponds to the manure management system PRP i.e., “Pasture/Range/Paddock” where manure is not managed (IPCC, 2019). We assumed the increase in beef productivity is related to better quality/quantity feed supply (dry matter intake). This is because the change from pastures with low nutrient levels to pastures which deliver a higher nutrient content via the integrated systems of trees and fodder. This better fodder improves the digestibility of dry matter and increase the nutritional value of the feed, in terms of total protein and minerals (Chará et al., 2019) (Pérez-López & Afanador-Téllez, 2017).

Moreover, sustainable cattle production also includes better animal welfare (disease management), better management of pastures, fodders, and soil quality. One of the sustainable cattle production systems suggested for Colombia is called the silvopastoral system which could contribute to improving soil conditions and increasing C-stock (CIAT & CORMACARENA, 2017) (Chará et al., 2019). The input data for calculating the GHG emissions of beef production for all scenarios are included in Table A4 in the Appendix. Considering that the IPCC 2019 methodology refined some of the default data according to high and low cattle productivity systems (IPCC, 2019), we assume the use of these default data (when available) to apply it to the scenarios according to the related best practices (see Table A4 in the Appendix).

4.2.6 GHG Emission Associated with Energy Crops

It is assumed that energy crops are cultivated, one at a time, on the surplus land obtained from the agricultural intensification described in section 2.4. The amount of energy crops that can be produced depends on the amount of surplus land generated in each scenario and the energy crop yield (see Table A7 in the Appendix). Since only in the medium and high scenarios large amounts of surplus land are obtained, energy crop cultivation is only evaluated for these two scenarios. The GHG emissions of energy crops include the emissions related to cultivation (fertilization and fossil fuel consumption) and to LUC. Emissions from fertilization include fertilizer production and direct/indirect

N2O emissions of fertilizer application (Table A7). The calculation of the GHG emissions of energy crop cultivation follow the same logic as for food crops, see section 2.5. In Table A3 and Table A7 of the Appendix, all input data and factor emissions for the calculations of the GHG emissions of energy crops cultivation are included.

4.2.7 GHG emission Related to Land Use Change

The expansion and contraction of agricultural land and the use of surplus land for energy crops results in changes in C-stock. Changes in C-stock were calculated for five different possibilities of LUC in the Orinoquia region as follows: considering that for the reference and low scenarios, the increase in agricultural land demand requires the use of natural vegetation (shrubland) and that forest is excluded for agricultural land use, the land-use conversions for these two scenarios are a) from shrubland to cropland for food crops production. b) From shrubland to pastureland in degraded pastures for cattle production (i.e., pastures with low nutrient levels). Note that in line with Rincon Castillo et al., (2012) and Rodríguez Borray et al., (2019), we assume that the land currently used for extensive cattle production is degraded. Therefore, the considered land-use conversions in the medium and high intensification scenarios are c) cropland to cropland for food crops and d) from degraded pastures to managed pastures for cattle production (beef). In the intensification scenarios, all the surplus land comes from cattle production areas (i.e., pastures with low nutrient levels). Therefore, for energy crops production the considered land use conversion is e) from degraded pasture to energy crops (sugarcane, oil palm, and acacia). GHG emissions caused by changes in C-stocks due to the LUC food crops were calculated using Equation (3).

$$E_{LULUC} = \Delta CS * 44/12 * 1/20 * 1/P$$

Equation 3

$$E_{LULUC} = (CS_R * 44/12 * 1/20 * 1/P) - (CS_A * 44/12 * 1/20 * 1/P)$$

Where, E_{LULUC} = GHG emissions from C-stock change due to LUC (t CO_2eq t^{-1} crop product). $\Delta CS = CS_R - CS_A$ (CS_R = C-stock associated with the prior land-use (t C ha^{-1}); CS_A = C-stock associated with the new land-use (t C ha^{-1}). P = crop productivity (t ha^{-1} $year^{-1}$). An amortization period of 20 years is assumed. The factor 44/12 is used to convert carbon into CO_2.

Each land use has a different carbon stock. The total C-stocks, including above and below ground biomass and SOC, of each land use type are included in Table 2. The time to be considered for changes in C-stocks was 20 years, in line with IPCC, (2019).

Table 2. Carbon stock including above and below ground biomass and SOC for various land use types in the Orinoquia region based on Castanheira et al., (2014), unless otherwise specified.

Land use type	**Total carbon stock (t C ha^{-1})**
Cropland	33
Shrubland	126
Degraded pastures for cattle production	50
Managed pastures for cattle production (medium/high scenario)	86/105
Oil palm (low/medium/high scenario) [a]	113/121/129
Sugarcane (medium/high scenario) [b]	62/65
Acacia (medium/high scenario) [c]	85/90

- Note that in this study, energy crops are only planted in surplus land of the medium and high scenario. The C-stock for energy crops in the medium scenario corresponds to the average between the C-stock of the low and the high scenario.

[a] Data for low scenario from (Henson, Ruiz R, & Romero, 2012). Note that in this study, oil palm is used both as a food crop and as an energy crop.

[b] High C-stock value from (Kerdan, Giarola, Jalil-Vega, & Hawkes, 2019). The low C-stock value (59.3) taken from (Lisboa, Butterbach-Bahl, Mauder, & Kiese, 2011).

[c] Data from (Matsumura, Nakama, Sukandi, & Imanuddin, 2007). The low C-stock value corresponds to 80 t C ha^{-1}.

4.2.8 Total GHG of Bioenergy Supply Chains

The total GHG emissions of sugarcane-bioethanol, palm oil-biodiesel, and acacia-bioelectricity include GHG emissions of energy crop cultivation, LUC, conversion plant (industrial production stage), and combustion (i.e., it refers to the conversion of biofuel to heat, electrical, or mechanical energy). For this study, it is assumed that the conversion plant for each bioenergy chain includes the following stages:

- For bioethanol, conversion plant includes cane transport, milling process, and ethanol plant (Mekonnen et al., 2018).
- For biodiesel, conversion plant includes palm oil mill, physical refining (refined, blanched, and deodorized); transesterification; esterification of the free fatty acid (FFA); BD purification; glycerin purification (USP), and methanol recovery (Ramirez-Contreras et al., 2020).
- For bioelectricity, conversion plant includes sawmill and pellet mill (Roder, Whittaker, & Thornley, 2015). It was assumed a CHP (combined heat and power) system for bioelectricity production. For the calculation, the stationary combustion emissions factor of the IPCC, 2019 (volume 2, chapter 2) was used.

Data and emission factors in the three-supply chain are presented in Table A8 of the Appendix. Note that for all three bioenergy supply chains, it was assumed that both the emissions in the conversion plant and the emissions from bioenergy use (combustion) do not vary in the scenarios, since the focus of this study is on the cultivation stage. Emissions from biomass combustion include emissions of methane (CH_4), and nitrous oxide (N_2O), but the biogenic CO_2 emissions of the crop biomass are considered carbon neutral.

The GHG emissions caused by changes in C-stocks due to the LUC energy crops were calculated using Equation (3). The net GHG emissions of the supply chain per bioenergy are calculated using Equation (4).

$$\boldsymbol{Net_{GHG} = F_C + LUC + CCS + F + B_{PE} + B_U} \qquad (4)$$

Where, F_C: Fossil fuel consumption emissions. LUC: Land use change emissions. CCS: Crops C-stock sequestration. F: Fertilizer emissions (production and application). B_{PE}: Bioenergy emissions by industrial production stage, B_U: Bioenergy emissions by use (combustion/burning).

Comparing the GHG emissions of the bioenergy production routes with the emissions from the fossil reference systems (gasoline, diesel, and coal; see Table A8 of the in Appendix), we evaluate the potential emission savings from bioenergy. Consequently, it is analyzed if the bioenergy GHG reduction levels meet the RED II GHG saving requirements.

4.3 Results

4.3.1 Agricultural Intensification

In the reference scenario, the total calculated land demand for food production in the Orinoquia region in 2030 is 13.8 Mha, of which about 90% is used for beef production in extensive cattle grazing system (Figure 4). Although this is still within the agricultural frontier area of 15.5 Mha, it is a little more than double the area currently in use for agriculture (6.8 Mha), due to the projected increase in demand. Compared to the reference scenario, there is 38% decrease in agricultural land use in the low scenario, 58% decrease in the medium scenario, and 70% decrease in the high scenario. In the medium and high scenario, the land for cattle production includes the land used to produce forage sorghum for improved beef production (491 and 496 thousand hectares, respectively).

In none of the intensification scenarios was surplus land obtained from food crops. Obtaining surplus land from agricultural intensification is only possible due to improvements in cattle productivity. In the low intensification scenario, there is not surplus land. In the medium scenario, it is possible to obtain 0.6 Mha of surplus land. In the high scenario, about 2.4 Mha of surplus land becomes available, which corresponds to 39% of the area currently used for cattle grazing (i.e., 6.2 Mha).

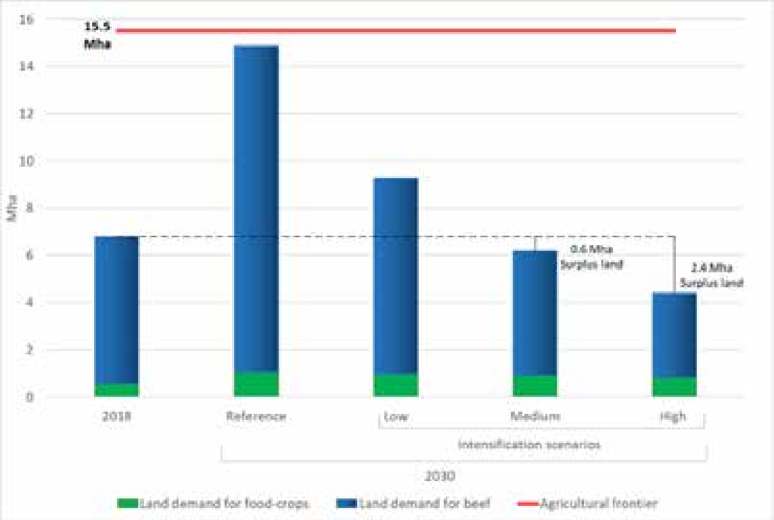


Figure 4. Total land requirement in the Orinoquia region to meet food crop and beef demand for all the scenarios in 2030 compared to agricultural land area in 2018.

For the medium and high scenario, the amount of energy cops and bioenergy that can be produced on surplus land is presented in Table 3. The highest bioenergy potentials are obtained when the surplus land is used to produce bioethanol from sugarcane or biodiesel from oil palm. This is due to the relatively higher ratio in the assumed conversion efficiency (MJ biofuel per kg raw material) of sugarcane and oil palm compared to acacia (i.e., one ton of FFB of oil palm produces 0.22 t of biodiesel with a calorific value of 37000 MJ t^{-1} biodiesel, while one ton of sugarcane produces 0.07 t of bioethanol with a calorific value of 27000 MJ t^{-1} bioethanol). In the high scenario, bioenergy potential is 3.8 to 5.4 times higher than in the medium scenario due to higher land availability and higher yield levels of the energy crops.

Table 3. Energy crop and bioenergy potential on surplus land in Orinoquia region in 2030 according for the medium and high intensification scenario.

		Medium scenario	High scenario
Sugarcane	Mt sugarcane yr^{-1}	52	201
Bioethanol	PJ yr^{-1}	96	368
Oil Palm	Mt FFB yr^{-1}	10	44
Biodiesel	PJ yr^{-1}	82	349
Acacia	Mt wood yr^{-1}	10	46
Bioelectricity	PJ yr^{-1}	36	162

4.3.2 GHG Emissions Associated with Agricultural Intensification

Figure 5 shows the annual GHG emissions of agricultural intensification (food crops and cattle) for all scenarios in 2030. LUC emissions result from the changes in C-stock due to land use change. The "LUC emissions" value in the figure considers both LUC emissions and C-stocks from food crops and pasture production for cattle. In the reference scenario, the largest GHG emission source is LUC which represents about 90% of the total GHG emissions of agricultural production (food crops and beef). The expansion of beef production is the main cause of LUC-related emissions (318 Mt CO_2eq yr^{-1}) due to the conversion of shrubland to degraded pastures (i.e., pastures with low nutrient levels). Regarding food crops in the reference scenario, the highest contribution to LUC emissions is related to the expansion of rice and oil palm (8.9 and 5.8 Mt CO_2eq yr^{-1}, respectively) due to the conversion of shrubland to cropland.

In the agricultural intensification scenarios, the LUC-related emissions are lower than in the reference scenario, but the low intensification scenario required the conversion of shrubland to degraded pastures to meet the demand for beef. Therefore, the LUC-related emissions in the low scenario are much higher than for the medium and high scenarios (191; 48; and 33 Mt CO_2eq yr^{-1}, respectively). For the medium and high scenario, no natural land is converted to agricultural land and degraded pastures are improved to managed pastures. Moreover, the carbon storage in the managed pastures (fertilized) will increase productivity and therefore also increase the C-stocks of those lands. The emissions of feed production, i.e., sorghum forage, is only reported for the medium and high scenarios (3.4 and 2.9 Mt CO_2eq yr^{-1}, respectively), as in these scenarios it is assumed that the quality of the animal feed was improved. These feed emissions include all emissions related to growing sorghum forage.

Note that, in agricultural production scenarios, the only two crops that report net carbon storage are oil palm and pastures. The oil palm cultivation to produce oil for human consumption is the only food crop that reports a net carbon sequestration as a perennial crop (i.e., negative LUC emissions) since the C-stock value considers the biomass of fronds, trunk and roots, the cover vegetation, and the associated organic matter that remains in the plantation after the harvest of the fruit (FFB). In the case of pastures to produce beef, the yield of beef production is directly linked with higher consumption of grass by cattle. For example, in the high scenario, total grass consumption is higher than in the reference scenario, but the demand for land to produce pastures is less in the high scenario compared to the reference scenario.

In the low, medium, and high scenario, the total (positive) emissions associated with food crop production (fertilization, fossil fuel, and CH_4 emissions at the field) and beef production (CH_4 emissions of enteric fermentation and manure, N_2O emissions) are lower compared to the reference scenario. For the medium and high scenario, the reduction of emission is a result of better management practices such as increasing the fertilizer efficiency, reducing the consumption of fossil fuels, and improving cattle feed quality. Regarding the efficiency of fertilizers, from the application of urea in the reference scenario, we move on to the application of more efficient sources of fertilizer to reduce NH_3 and N_2O emissions by application and volatilization of fertilizers as described in the Appendix B. Regarding fossil fuel, the emission reduction is given mainly by the diesel reduction used by machinery (i.e., higher efficiency).

Regarding cattle feed quality, it is observed that with no change in quality animal feeding, as the number of animals increases, the CH_4 emissions from enteric fermentation could increase, as observed between the current situation (2018) and the reference scenario (10.7 and 17.7 Mt CO_2eq yr^{-1}, respectively). However, with a better-quality feed, the number of animals and their CH_4 emissions by enteric fermentation would be reduced while the animal-beef ratio would be increased, as observed in the medium and high scenario (15.3 and 13.7 Mt CO_2eq yr^{-1}, respectively). When agricultural production intensifies sustainably (i.e., high scenario), there is a reduction in positive emissions of 83% compared to the reference scenario.

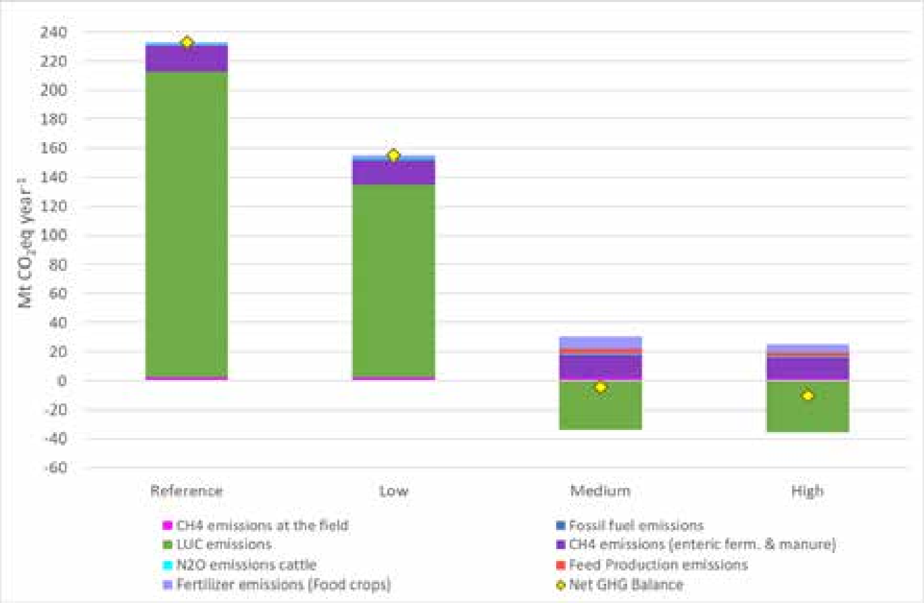


Figure 5. Net GHG emissions associated with agricultural intensification (food crops and beef) in the Orinoquia region for all scenarios in 2030.

4.3.3 GHG Emissions Associated with Bioenergy Production

The net GHG emissions of bioenergy production and abated emissions compared to their fossil fuel equivalent for the medium and high scenario in 2030 are shown in Figure 6. For all bioenergy supply chains, the net GHG emissions are slightly higher in the high scenario than in the medium scenario, due to the use of better agricultural practices in the cultivation stage. For all bioenergy supply chains, the GHG emissions related to LUC dominate the GHG balance. Negative LUC emissions (sequestration) vary among bioenergy supply chains because the tree energy crops store much more carbon than the original vegetation present today (i.e., pastures with low nutrients). The LUC emissions from the oil palm crop behave the same as those described in section 3.2, agricultural intensification.

For both scenarios, the emissions in the conversion of biomass to energy carriers of the three bioenergy chains are lower than the cultivation emissions, as shown in Table 4. The emissions from the use of biofuels (i.e., N_2O and CH_4 emissions by combustion) are the same for both biodiesel and bioethanol (0.3 g CO_2eq MJ^{-1} biofuel) and higher for bioelectricity (i.e., burning of acacia pellets) (1.9 g CO_2eq MJ^{-1} bioelectricity). Logically, under the high scenario, more surplus land is available for bioenergy production than in the medium scenario (2.4 and 0.6 Mha, respectively) and subsequently, the emissions related to each energy crop production system are in line with the quantity of raw material produced (PJ bioenergy yr^{-1}). For example, the high scenario with biodiesel production reports a higher net GHG balance (-82.5 g CO_2eq MJ^{-1} biofuel) than the high scenario with bioethanol production (-6 g CO_2eq MJ^{-1} biofuel) as shown in Figure 6(a).

Table 4. Emissions of bioenergy production for the medium and high intensification scenario.

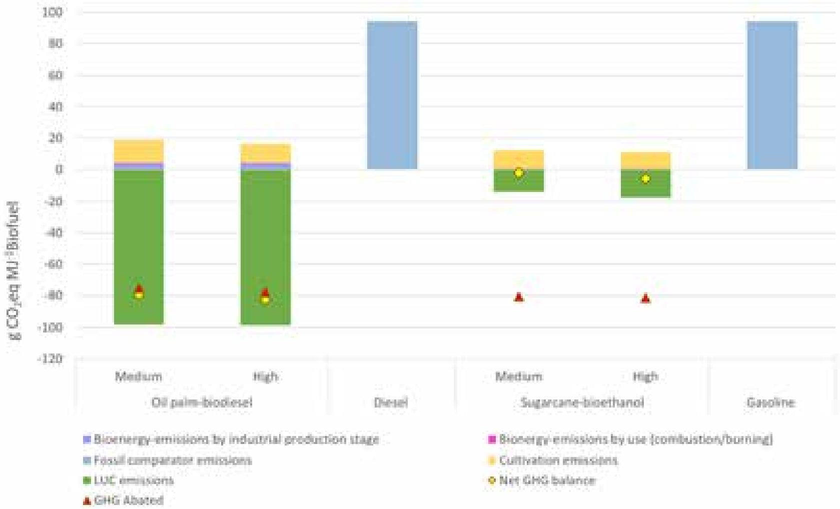
			Medium scenario	High scenario
Sugarcane	Cultivation stage	g CO_2eq MJ^{-1} biofuel	11.7	10.9
	Industrial stage	g CO_2eq MJ^{-1} biofuel	0.2	0.2

Oil Palm	Cultivation stage	g CO_2eq MJ^{-1} biofuel	14.6	12.0
	Industrial stage	g CO_2eq MJ^{-1} biofuel	3.9	3.9
Acacia	Cultivation stage	g CO_2eq MJ^{-1} bioelectricity	27.6	23.9
	Industrial stage	g CO_2eq MJ^{-1} bioelectricity	0.0007	0.0007

The total GHG emissions of biofuels and bioelectricity production, including the emissions related to LUC, cultivation (fertilization and diesel use), conversion and direct use, are compared to their fossil counterpart to calculate the abated emissions (Figure 6). Bioethanol, biodiesel, and bioelectricity production achieve more than 100% emission reduction compared to their fossil fuel equivalent. They thereby meet the RED II GHG saving requirements, which is 65% for biofuels (i.e., bioethanol and biodiesel) and 70% for bioelectricity.

In this study, the emissions resulting from the combustion biofuels in vehicle engines are not calculated, since CH_4 and N_2O emissions are highly dependent on the efficiency of the source technology, emission control, and combustion system that is not the core of this study. However, to identify whether the abated emission could be affected by the combustion of the biodiesel in an engine, we applied the brake thermal efficiency (BTE) of the computerized diesel engine reported by Soly et al. (2021), to the emissions from the biodiesel chain reported in our study (BTE is defined as the ratio of brake power of an engine and the energy of the fuel released during the combustion process. Soly et al. (2021) found a BTE of 25.3% for diesel and 25.6% for biodiesel). As a result, the calculated abated emissions by the use of biodiesel, reported in our study, are affected by up to 1.3%.

A.



B.

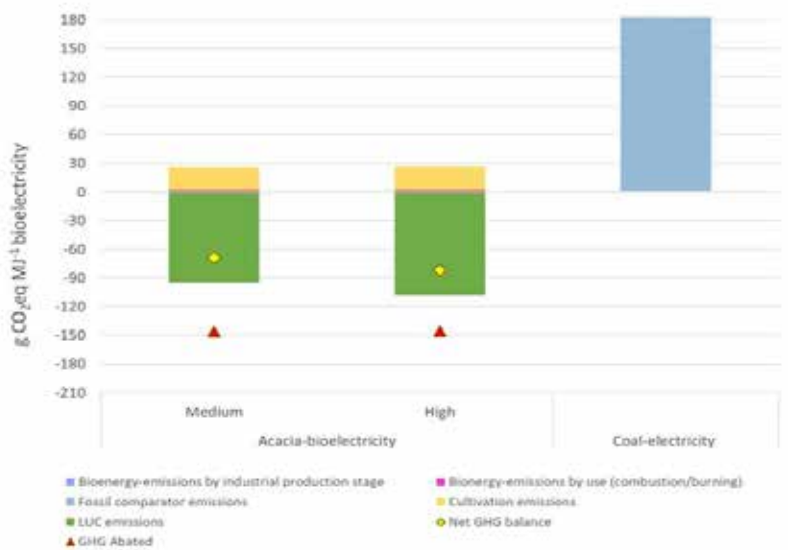


Figure 6. Net GHG emissions of bioenergy production and abated emissions compared to their fossil fuels equivalent for the medium and high scenario in 2030.

4.3.4 Regional GHG Balance of Agricultural Intensification & Bioenergy Production

The GHG balance on the entire regional level, for both the agricultural intensification and bioenergy production, is shown in Figure 7. Increased agricultural yields, use of better agricultural practices, and use of surplus land for bioenergy production result in a decrease in net GHG emissions in the medium and high scenario compared to the reference and low scenario, and the current situation (2018). When comparing the net emissions of the reference and low scenario with the emissions of the current situation (2018), the emissions of the low scenario are slightly higher than in 2018 (153 and 141 Mt CO_2eq yr^{-1}, respectively). However, the emissions of the reference scenario (231 Mt CO_2eq yr^{-1}) are 65% higher than the net emissions of 2018. In Figure 7, the results show that it is feasible to produce bioenergy on surplus land obtained from agricultural intensification (i.e., medium and high scenario), reducing the total emissions of the region and contributing to the increase in carbon sequestration with the use of any of the three energy crops raised in this study.

The abated emissions are logically higher in the high scenario compared to the medium scenario for all energy crops because of the larger amounts of raw material produced on surplus land in the high scenario. Also, it must be considered that the LUC emissions (sequestration) are calculated over 20-year lifetime period for all the crops, then the LUC benefit can only be gained during that period. However, if that crop lifetime is extended more benefits could be obtained from the LUC-related emissions.

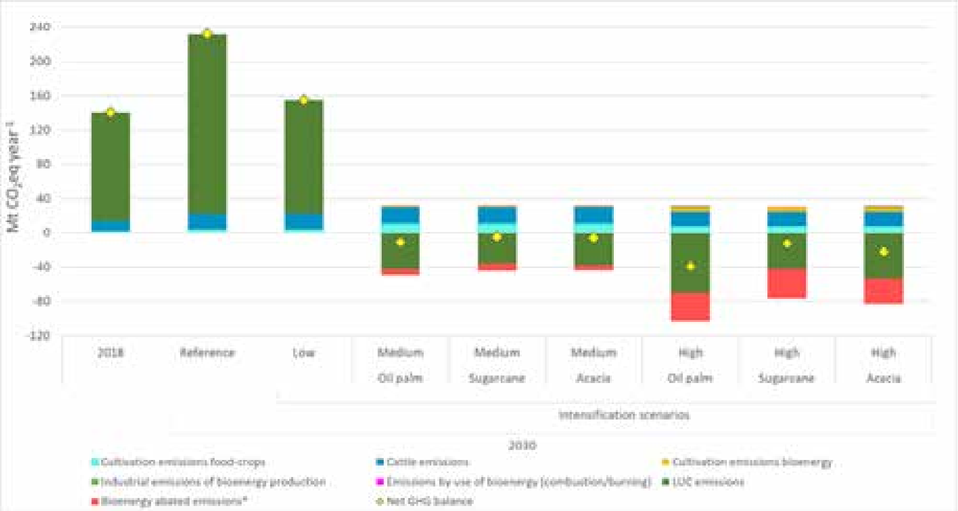


Figure 7. GHG balance of agricultural intensification (food crops and beef) and bioenergy production in 2030 for all scenarios. It is assumed that energy crops are only cultivated on surplus land obtained in the medium and high scenario. Note that bioenergy abated emissions do not include abated LUC emissions.

4.4 Discussion

In this study, we calculated the GHG balance of increasing agricultural yields for food crop and beef production and using the generated surplus land for biomass production to replace fossil fuels for a key region in Colombia. The results highlight that sustainable intensification is a key measure to reduce GHG emissions associated with agriculture in the region and to produce low-ILUC-risk bioenergy. Furthermore, since the surplus land is projected to come largely from improving extensive cattle farming areas with low carbon stocks and bioenergy crops have higher carbon stocks, bioenergy production contributes to carbon stock increase. However, there are many uncertainties related to the assumptions and data used to calculate the overall GHG balance, which affects the results obtained, as discussed next.

Region-specific carbon stock measurements are needed. Depending on the soil type and its initial c-stock, variations in carbon stocks can impact the LUC-related emissions to a greater or lesser extent. It has been reported that the Orinoquia savanna lands have a carbon stock of around 126 t C ha^{-1} (Castanheira et al., 2014). If this land is converted to cropland with a low carbon stock, it results in high GHG emissions. However, due to lack of field measurements, there is large uncertainty on the carbon stocks of the various land uses in the region (Castanheira et al., 2014) (Lavelle et al., 2014) (Silva-Parra, 2018) (Quezada et al., 2019) (Escribano, Elghannam, & Mesias, 2020). For example, a study conducted in the Orinoquia's highplain showed that carbon stocks did not change with the conversion of managed grasslands to oil palm plantations (Quezada et al., 2019). The study also highlighted that the conversion of pastureland (i.e., degraded pastures) to perennial energy crops could benefit the ecosystem carbon storage (both soil and biomass carbon stock) (Quezada et al., 2019). Thus, the conversion of surplus land from degraded pastures (i.e., pastures with low nutrient levels) to energy crops could potentially generate greater soil and biomass carbon sequestration than converting it to improved pasture. A key requirement to achieve energy crop sustainability is to avoid the negative impacts that expansion of these crops could generate in the region (Rincón et al., 2014) (Lavelle et al., 2014) (Quezada et al., 2019). First, reducing ILUC risks of energy crop requires sustainable intensification of the current agricultural production. Second, sustainable energy crop production is not only about carbon sequestration but also about biodiversity and water availability.

Third, the conversion of native savanna results in considerably increased LUC-related emission; its use for bioenergy crop production is therefore to be avoided because of the high indirect GHG emissions issues, it could cause.

Increasing current cattle productivity is key to reduce future agricultural land demand and associated GHG emissions. Increasing cattle productivity requires a set of management improvements (i.e., quantity of feed supplied, forage type, and forage quality) (Rincón Castillo & Jaramillo, 2010) (Rincón Castillo & Flórez Díaz, 2013) (Fedegan, 2020). The implementation of those improvements over time is still a key topic for further research and will depend on support measures for the sector. In the Orinoquia region, the increased land demand leads to increased LUC emissions as shrubland (natural savannas) became pastureland. Therefore, a sustainable increase in cattle productivity would decrease land demand, increase the amount of beef produced, and decrease LUC-related emissions. Moreover, improvement in the nutrition of cattle feed also contributes to the GHG emissions reduction (Rincón Castillo & Jaramillo, 2010) (Rincón Castillo & Flórez Díaz, 2013).

To warrant low LUC-related emissions, more refined knowledge about the future location of surplus land is required. In this study, the location of the agricultural areas of the region was not considered. Only the amount of land used to produce both food crops and cattle was considered. Therefore, it is not possible to spatially identify the areas where the surplus land for the cultivation of energy crops is located. Just as specific measurements of carbon stocks in the region are required, it is also necessary to establish the location of current agricultural areas, particularly areas with an extensive cattle production system. This way the uncertainty of the related-LUC emissions could be reduced and facilitate the application of agricultural intensification measures. Another key point to reduce the uncertainty of emissions in cattle production is related to the quality of emission data of the different management levels of cattle. In this study, we use the factors updated by the IPCC in the 2019 refinement, which included data for Latin America. However, identification of national or regional emission factors could contribute to establishing more accurate results of emissions from cattle production.

4.5 Conclusions

In this study, the total GHG balance of future agricultural land use in the Orinoquia region was analyzed for different agricultural intensification scenarios and using the generated surplus land for energy crops. The total land requirement in the Orinoquia region to meet the demand for food crops and beef in 2030 shows an increase of a little more than double the land in the reference scenario compared to the demand for land in 2018. The largest land demand in the reference scenario is for beef production in extensive grazing systems, occupying more than 90% of the agricultural area. Although the land demand in the reference scenario is within the available agricultural land (agricultural frontier) of the region, it requires the conversion of shrubland to pastureland and causing large amounts of LUC-related emissions.

In the medium and high intensification scenario, less area is required to produce the same amount of food compared to 2018 due to an increase in agricultural productivity. The increase in cattle productivity is key to release between 10% and 38% of the current cattle production area for bioenergy feedstock production. The medium and high agricultural intensification scenarios result in decreased LUC-related emissions compared to the reference scenario, since no natural vegetation (shrubland) is converted, and degraded pastures are improved to be used as managed pastureland. The application of better agricultural practices when intensifying agricultural production can reduce up to 83% of the positive GHG emissions of the reference scenario.

Bioenergy potential production on the surplus land obtained is projected at 36 to 368 PJ per year been considered as low-ILUC-risk because using surplus land minimizes concerns related to competition for land and displacement effects. As the cattle areas that generated surplus land are expected to consist largely of degraded pastures, the conversion of degraded pastures to energy crops can result in substantial carbon sequestration. Moreover, bioenergy production (biodiesel, bioethanol, or bioelectricity) as the bioenergy options assessed results in a reduction in GHG emissions of more than 100% compared to its fossil fuel equivalent (diesel, gasoline, and coal, respectively), meeting the RED II GHG saving requirements. Our study focused only on GHG emissions, but sustainable intensification of crops and cattle production as well as bioenergy feedstock production also requires assessment of other environmental and socio-economic impacts of agricultural intensification and bioenergy production. This will be tackled in follow-up work being carried out by Ramirez-Contreras et al. (2021).

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Appendix

A. Parameters for calculation of the agricultural land demand

Table A-1. Data inputs for estimation of required food production in the Orinoquia region of Colombia in 2030.

	Per capita consumption[a] (kg/person/year)		**SSR**[b] (%)	**Food losses**[b] (%)	**Contribution**[c] Orinoquia to national production (%)	**Land use** in the region (ha) 2018 [c]
	2018	2030				
Population Colombia[d]	48,258,494	55,678,083				
Rice	42.2	42.2	90	28	50	176,391
Oil palm (CPO)	33.3	35.0	106	19	40	178,227
Corn	30.2	31.0	33	28	50	57,387
Plantain	53.6	68.0	102	55	30	78,673
Soybean	35.7	37.5	23	19	90	37,340
Cassava	38.5	38.5	99	40	30	18,912
Beef	18.9	24.0	105	22	.	6,239,309

[a] Per capita consumption data from (MADR, 2016) (OECD-FAO, 2019) (Fedearroz, 2019) (Fedegan, 2019) (Younis et al., 2020).

[b] Based on data from (Younis et al., 2020) and (MADR, 2016). SSR relates domestic food production with imports and exports of food products. Thus, SSR values greater than 100% indicate large export quantities while SSR values lower than 100% express large import quantities (Younis et al., 2020). The projected food consumption is based on assuming that Colombia follows the general trend of Latin America for 2030 (MADR, 2016). The SSR, food losses, and the contribution of Orinoquia to national food production is assumed to be the same in 2030 as in 2018.

[c] Data from (Agronet, 2019).

[d] Data from (DANE, 2019c).

B. Parameters for calculation of GHG emissions associated to agricultural intensification

- **Agricultural intensification levels**

Agricultural production in the Orinoquia region requires sustainable intensification to reduce GHG emissions while increasing food production (food crops and beef). The efficient use of fertilizers, reduction of fossil fuel consumption, and reduce the impact of LUC are related as some of the better agricultural practices known for their potential to reduce GHG emissions. See input data for food crops in Table A-2 and input data for cattle production in Table A-4. The intensification levels are based on the study by (Gerssen-Gondelach et al., 2017) and listed below:

i) *Conventional agricultural practices*:

- For crops: it refers to the traditional production in the foothill-highplain area, where the agricultural practices are not enough improved to increase crop yield (i.e., fertilizer are applied without including soil requirements; no soil correction is made). Soil correction is adapting the soil to establish or maintain a crop. In the Orinoquia, the main limiting factor for soils is acidity, then lime or another product is added to improve chemical deficiencies (Rincón Castillo & Jaramillo, 2010) (Fedearroz, 2011) (Amézquita, Rao, Rivera, Corrales, & Bernal, 2013). Generally, corrective measures are applied before planting activities that is why prior soil analysis is essential to detect these problems and formulate appropriate corrective applications (UPRA, 2019).

- For beef production: this is the extensive cattle production system currently used in the foothill-highplain area, where cattle are fed only with natural grassland with low nutrient content. This grassland has not received fertilization.

ii) *Intermediate intensification*:

- For crops: it allows increasing crop yields with the improvement of some agricultural practices (i.e., fertilizer is applied according to the soil requirements, but no soil correction is made; adequate soil conditioning is not done).
- For beef production: it is an improved extensive production system. Cattle are fed with improved grasses (e.g.., *Brachiaria decumbens*) and forage sorghum (fertilizer is used for improved grasses and forage sorghum). The forage sorghum is mainly used during dry season to complete the cattle feed.

iii) *Sustainable intensification*:

- For crops: this pathway uses better agricultural practices to increase crop yield (i.e., fertilizer is applied according to the soil requirements; soil correction is made; grasses/legume are used; zero tillage is done).
- For beef production: Animal increase in productivity is attained by the improvement of feed quality supplied since the animal feed is based on improved grasses (e.g.., *Brachiaria decumbens*) and forage sorghum. The forage is used to supply the needs in during the dry season (fertilizer is used for improved grasses and forage sorghum). It is assumed that for this sustainable scenario the grazing system is silvopastoral or agrosilvopastoral.

- **Fertilization**

The use of nitrogen fertilizers causes GHG emissions (Woodbury & Wightman, 2017). Nitrogen fertilizer urea (N) releases nitrous oxide (N_2O) and ammonia (NH_3) during its application. About 25% of the urea applied to a crop volatilizes as NH_3, of which about 1-2% is subsequently converted to N_2O. The reduction of NH_3 and N_2O emissions depends on increasing the efficiency of nitrogen fertilizer use, which includes both the use of good agricultural practices and the use of slow-release nitrogen fertilizers (Wang, Sarah, & Klaus, 2020). Therefore, we assumed that to reduce emissions by application and volatilization of fertilizers, in the high scenario, more efficient sources of fertilizer are used. Below are the nutrient sources used by scenario:

- *Reference, low,* and *medium* scenario: Urea, as N; DAP (diammonium phosphate), and KCl (potassium salt).
- *High* scenario: Controlled release nitrogen fertilizer, as N; TSP (triple super phosphate), and KCl (potassium salt).

- **Emission factors (EF)**

Table A-2 and Table A-3 show the input data and emission factors associated to crops production. Only chemical fertilization was considered. Organic fertilization was not considered. The EF of fertilizer production were taken from Ecoinvent database, version 3.0.1.0. For all crops, emission calculations include LUC emissions over twenty years following IPCC 2019 guidelines (IPCC, 2019). The N_2O emissions from managed soil were calculated based on the IPCC methodology (IPCC, 2019) and following the *Equation A-1* and *Equation A-2*. The emissions factor of diesel production and diesel-burning by use are assumed based on IPCC guidelines (IPCC, 2019).

$$N_2O_{Direct} = F_{SN} * EF_1 * 44/28$$ **Equation A-1**

$$N_2O_{Indirect} = (((F_{SN} * Frac_{GASF}) * EF_4) + ((F_{SN} * Frac_{LEACH}) * \ EF_5) * 44/28$$ **Equation A-2**

Where: F_{SN} = annual amount of synthetic N-fertilizer applied (kg N t^{-1}). EF_1 = emission factors for N_2O emissions from N inputs [kg N_2O–N (kg N input)$^{-1}$]. $Frac_{GASF}$ = fraction of synthetic fertilizer N that volatilizes as NH_3 and NOx [(kg N volatilized (kg of N applied)$^{-1}$]. $Frac_{LEACH}$ = fraction of all N added to/mineralized in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff [kg N (kg of N additions)$^{-1}$]. EF_4 = emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces [kg N–N_2O (kg NH_3–N + NOx–N volatilized)$^{-1}$]. EF_5 = emission factor for N_2O emissions from N leaching and runoff [kg N_2O–N (kg N leached and runoff)$^{-1}$]. 44/28 = Conversion of N_2O–N emissions to N_2O emissions for reporting purposes.

Table A-2. Input data for food crops stage in the reference and intensification scenarios.

Scenarios [a]	Food crop	Nutrient (kg ha^{-1})			Diesel usage (liters t^{-1}) [d]
		N [b]	P_2O_5	K_2O	
Reference	Rice	110	36	157	25.10
	Corn	121	50	126	2.73
	Oil palm [c]	78	24	163	4.92
	Plantain	47	6	65	8.33
	Soybean	200	46	99	16.20
	Cassava	56	14	53	1.96
Low	Rice	140	46	200	24.26
	Corn	165	69	172	2.64
	Oil palm	108	33	224	4.76
	Plantain	72	10	100	8.05
	Soybean	253	58	126	15.66
	Cassava	75	18	71	1.89
Medium	Rice	123	40	175	23.45
	Corn	143	59	148	2.55
	Oil palm	92	28	190	4.60
	Plantain	65	9	90	7.78
	Soybean	240	55	119	15.14
	Cassava	81	19	75	1.83
High	Rice	138	45	196	22.67
	Corn	165	69	172	2.46
	Oil palm	104	32	214	4.44
	Plantain	90	12	125	7.52
	Soybean	243	56	121	14.63
	Cassava	89	21	83	1.77

[a] For all scenarios. fertilization data to each crop were calculated based on data from (IPNI, 2002).

[b] The annual amount of synthetic N-fertilizer applied to crops also correspond to F_{SN} value in *Equation A-1* and *Equation A-2*.

[c] For oil palm crop, the amount of fertilizer is expressed per ton of fresh fruit bunches (FFB).

[d] Diesel consumption for the reference scenario is based on literature as follow: data for rice taken from (Alam, Bell, & Biswas, 2019); for corn (Yang & Chen, 2013); for oil palm (N. E. Ramirez-Contreras et al., 2020); for plantain (Jekayinfa, Ola, Afolayan, & Ogunwale, 2012); for soybean (Castanheira, Grisoli, Coelho, Anderi Da Silva, & Freire, 2015); for cassava (Jiao, Li, & Bai, 2019). For the intensification scenarios, it was assumed that diesel consumption would decrease from the reference scenario until reaches a reduction up 10% in the high scenario. This reduction is being considered based on the study by (Brinkman et al., 2018).

Table A-3. Emission factors for all type of crops (food, energy, and feed) in the cultivation stage in the reference and intensification scenarios.

- **Fertilizer production emission factors:**	Unit	EF
Urea as N (0.46% N) [a]	kg CO_2eq/kg Fertilizer	3.38
Ammonium sulphate (SAM) as N (0.21% N) [a]		2.79
Diammonium phosphate (DAP) as P_2O_5 [a]		1.61
Potassium chloride as K_2O [a]		0.53
Triple super phosphate (TSP) [b]		0.34
Controlled release nitrogen fertilizer as N (0.46% N) [c]		2.79

• **Field N_2O emission factors [d]**		
F_{SN} (annual amount of synthetic N-fertilizer applied)	kg N ha^{-1}	correspond to values listed in the column for N-nutrient
$Frac_{GASF}$ (fraction of synthetic fertilizer N that volatilizes as NH_3 and NO_X)	kg N volatilized (kg of N applied)$^{-1}$	0.11
$Frac_{LEACH}$ (fraction of all N added to/mineralized in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff	kg N (kg of N additions)$^{-1}$	0.24
EF_1	kg N_2O–N (kg N)$^{-1}$	0.01
EF_4	kg N_2O–N (kg NH_3–N + NO_X–N volatilized)$^{-1}$	0.01
EF_5	kg N_2O–N (kg N leaching/runoff)$^{-1}$	0.011
• **Fossil fuel emission factors [e]**		
Diesel production	kg CO_2 /kg diesel	0.569
Burning diesel	kg CO_2 /kg diesel	3.188
	kg CH_4 /kg diesel	0.00045
	kg N_2O /kg diesel	0.00008

[a] Emission factors for fertilization production are taken from Ecoinvent database, version 3.0.1.0.
[b] Data from (Alam et al., 2019).
[c] Controlled release nitrogen fertilizer as N (0.46% N), was assumed to report a lower production emission factor compared to Urea. Therefore, the emission factor of the lowest nitrogen fertilizers (SAM) is applied.
[d] Emission factors for N_2O emissions calculation (direct/indirect) resulting from N-fertilization were taken from (IPCC, 2019).
[e] Fossil fuel emission factor were taken from (IPCC, 2019).

- **Beef production**

In this study, we differentiate three categories of cattle based on the IPCC, 2019 classification: growing cattle, other mature cattle, and mature double-purpose cattle. It is assumed that the composition of the herd remains constant over time and is the same for all scenarios. The description of each category is as follows,

- Growing cattle: it includes calves pre-weaning, growing/fattening cattle. It is estimated 18% of animals in the herd correspond to this category (Fedegan, 2019).
- Other mature cattle: it includes male used to produce meat, breeding, and draft purposes. It is estimated 28% of animals in the herd correspond to this category (Fedegan, 2019).
- Mature double-purpose cattle: it includes the cows used to produce the cattle for beef, also produce milk for raising the growing cattle and other purposes. It is estimated 54% of animals in the herd correspond to this category (Fedegan, 2019).

The cattle production system (i.e., extensive grazing, improved extensive grazing, and silvopastoral grazing) varies according to the scenarios, as described in section 3.3 on agricultural intensification. When IPCC, 2019 does not require split up the cattle categories or when there are no specific values for a specific cattle category, we consider the closest value that resembles those that can be reported (see footnotes in the tables). Input data in Table A-4.

Table A-4. Input values for the calculation of GHG emissions of beef production in the reference and intensification scenarios.

Input data	Unit	Scenarios 2030			
		Reference	Low [p]	Medium [q]	High [q]
Animal density [a]	AU ha^{-1}	0.6	1.0	1.5	2.0

Animal population [b]	heads of cattle	9,331,160	9,064,783	8,317,333	7,110,636
Subcategories of cattle [c]					
Growing cattle	heads	1,662,006	1,614,561	1,481,430	1,266,501
Other mature cattle (beef)	heads	2,638,502	2,563,181	2,351,830	2,010,621
Mature double-purpose cattle	heads	5,030,652	4,887,042	4,484,074	3,833,515
Beef extraction factor [d]	%	52.5	52.5	53.0	53.0
Extraction rate [e]	%	17.5	17.5	18.2	20.0
TAM (typical animal weight) [a]					
Growing cattle	kg animal^{-1}	144	144	200	220
Other mature cattle	kg animal^{-1}	350	380	425	485
Mature double-purpose cattle	kg animal^{-1}	380	383	388	399
Total daily dry matter intake (DMI) [f]					
Growing cattle	kg day^{-1} animal^{-1}	4.7	4.7	6.2	6.5
Other mature cattle		8.6	9.0	9.7	10.5
Mature double-purpose cattle		8.8	8.8	8.9	9.1
Data for feed intake estimates					
Estimated dietary net energy concentration of the feed (Ne_{mf}) [g]	MJ kg^{-1} dry matter^{-1}	4.5	4.5	6.0	7.0
Gross energy intake (GE) [h]					
Growing cattle	MJ kg^{-1} dry matter	86.4	86.4	114.0	119.8
Other mature cattle		159.3	166.9	178.3	193.5
Mature double-purpose cattle		162.1	162.9	164.3	167.3
Methane (CH_4) emissions from enteric fermentation					
CH_4 conversion factor (Y_m) [i]	%	7	7	6.3	6.3
Methane (CH_4) emissions from manure management					
Volatile Solid excretion rate [j] ($VS_{T,P}$)	kg VS (1000 kg animal mass)$^{-1}$ day^{-1}	8.6	8.6	8.5	8.1
Fraction of total annual VS for each livestock species/category T that is managed in manure management system S in the country, for productivity system P, animal waste management systems (AWMS) [k]	Dimensionless	0.92	0.92	0.92	0.92
Emission factor for direct CH_4 (EF) [l]	g CH_4 kg VS^{-1}	0.6	0.6	0.6	0.6
N_2O emissions from manure management					
Nitrogen excretion rate (N_{rate}) [m]	kg N (1000 kg animal mass)$^{-1}$ day^{-1}	0.29	0.29	0.31	0.36
Annual N excretion (Nex) [n]					
Growing cattle	kg N animal^{-1} yr^{-1}	15.24	15.24	22.63	28.91
Other mature cattle		37.05	40.22	48.09	63.73
Mature double-purpose cattle		40.22	40.54	43.90	52.43
EF_3 to estimate direct N_2O emissions from managed soils [o]	kg N_2O-N (kg N)$^{-1}$	0.006	0.006	0.006	0.006
[a] Data from (Fedegan, 2006) (Fedegan, 2018a)					

[b] Animal population data was calculated considering the beef requirement per year, animal unit per ha, beef extraction factor, and extraction rate per scenario.
[c] The cattle population was classified into three main subcategories according to (IPCC, 2019) and it was considered the share for each category according to the information taken from (Fedegan, 2019).
[d] It is the percentage of carcass beef with respect to the live animal's weight. Data from (Fedegan, 2006) (Fedegan, 2019)
[e] It correspond to the percentage of the annual quantity of slaughtered beef cattle, Data from (Fedegan, 2006) (Fedegan, 2019)
[f] Own calculations based on the animal live-weight per categories and its relationship with the daily dry matter intake.
[g] Considering that in Table 10.8a in chapter 10 of IPCC, 2019, the diet quality can be selected, we assumed low quality diet in the reference and low scenario. Moderate quality diet for medium scenario and high-quality diet for the high scenario. Then, average default values from table 10.8a are selected (IPCC, 2019).
[h] GE was calculated by multiplying the DMI value by the default value of 18,45 MJ kg-1 of dry matter (IPCC, 2019)
[i] The Ym value of 7.0 is apply in reference and low scenario assuming non-dairy animal category and the non-feedlot diets (low quality pasture). The Ym value of 6.3 is apply in the medium and high scenario assuming high quality forage diets (IPCC, 2019).
[j] Default values for volatile solid excretion rate from Table 10.13A of the chapter 10 for Latin America region from (IPCC, 2019). For the reference and low scenario, it was selected “low PS for other cattle”. For the medium scenario, it was selected “means value for other cattle”. For the high scenario, it was selected “High PS for other cattle”.
[k] Default values in chapter 10 from (IPCC, 2019)
[l] Default values in chapter 10 from (IPCC, 2019). Methane emission factor for all animals in low and high productivity under a pasture, range, and paddock manure managed system.
[m] Default values from Table 10.19 of the chapter 10 for Latin America region from (IPCC, 2019). For the reference and low scenario, it was selected “low PS for other cattle”. For the medium scenario, it was selected “means value for other cattle”. For the high scenario, it was selected “High PS for other cattle”.
[n] Calculated with Equation 10,30 (IPCC, 2019)
[o] Default value for wet climates from Table 11,1 in chapter 11 from (IPCC, 2019)

a) Emissions from feed production (CO_2, N_2O)

It is assumed that during the dry season, sorghum forage is consumed as part of the animal feed for the medium and high scenarios. Sorghum emissions are calculated as for food crops. The grain sorghum yield is 4.8 and 5.16 t ha^{-1} $year^{-1}$ for the medium and high scenario, respectively (Agronet, 2019). The yield of the entire plant i.e., grain, leaves, and stalks was estimated at 55.5 t ha^{-1} $year^{-1}$ (Coblentz & Phillips, 2004). LUC emissions are from degraded pastureland to annual cropland. Input data in Table A-5.

Table A-5. Input data for sorghum forage for the medium and high scenarios

Scenario	Nutrient (kg ha^{-1}) [a]			Diesel usage [b] (liters t^{-1})
	N	P_2O_5	K_2O	
Medium	90	83	23	5.43
High	97	89	24	5.25

[a] Data base on (Coblentz & Phillips, 2004).
[b] Diesel usage data from (Maraseni, Chen, Banhazi, Bundschuh, & Yusaf, 2015).

b) Methane emissions from enteric fermentation

The methane emissions from enteric fermentation from cattle production are calculated according to the Tier 2 approach of the IPCC guidelines (2019). See *Equation A-3* (Eq. 10.20 of IPCC 2019):

$$Total\ CH_{4\ Enteric} = \sum_{i,P} E_{i,P} \qquad \textbf{Equation A-3}$$

Where,

Total $CH_{4\ Enteric}$ = Total methane emissions from enteric fermentation in Gg CH_4 yr^{-1}. $E_{i,P}$ = Methane emissions per cattle category i per production system P.

The methane emissions from enteric fermentation per cattle category per production system, are calculated according to *Equation A-4* (eq. 10.21 of IPCC 2019).

$$E = \frac{GE \cdot \frac{Y_m}{100} \cdot 365}{55.65}$$ **Equation A-4**

Where,

E = Methane emission, kg CH_4 head^{-1} yr^{-1}. GE = Gross energy intake, MJ head^{-1} day^{-1}. Y_m = Methane conversion factor, % of gross energy in feed converted to methane. The factor 55.65 (MJ/kg CH_4) is the energy content of methane.

To calculate the gross energy intake per head per day (GE), the dry matter intake (DMI) is multiplied by the default energy content of feed from the IPCC (2019), see *Equation A-5*.

$$GE = DMI * 18.45$$ **Equation A-5**

Where,

GE = gross energy intake, MJ head^{-1} day^{-1}. DMI = dry matter intake kg head^{-1} day^{-1}; 18.45 = default value to convert feed intake from mass to energy (IPCC, 2019).

The DMI per head per day varies across cattle categories and production system and relates to the live body weight and diet of the cattle, see *Equation A-6* for “growing cattle” (equations 10.18 of IPCC 2019). For other mature cattle and double-purpose cattle, we assumed the use of *Equation A-7* (equation 10.18A of IPCC 2019).

$$DMI = BW^{0.75} \cdot \left[\frac{\left(0.0582 \cdot NE_{mf} - 0.00266 \cdot {NE_{mf}}^2 - 0.0869\right)}{0.239 \cdot NE_{mf}}\right]$$ **Equation A-6**

Where,

DMI = dry matter intake, kg day^{-1}; BW = live body weight, kg; NE_{mf} = estimated dietary net energy concentration of the feed with default values in Table 10.8a of chapter 10, IPCC, 2019 in MJ kg^{-1} DM^{-1}.

$$DMI = 3.83 + 0.0143 * BW * 0.96 \text{ (other mature cattle)}$$

$$DMI = 3.184 + 0.01536 * BW * 0.96 \text{ (double-purpose cattle)}$$ **Equation A-7**

Where, DMI = dry matter intake, kg day^{-1}; BW = live body weight, kg.

c) Methane emissions from manure management

For all scenarios, it is estimated that cattle production is run on a grazing system where manure deposited on pasture. According to IPCC 2019 method, it corresponds to the manure management system “Pasture/Range/Paddock” (PRP) (IPCC, 2019). In this system, to estimate CH_4 produced from manure deposited on pasture, the manure management includes both dung and urine. When manure is deposited on pastures, rangelands or paddock less CH_4 is produced since it tends to decompose under aerobic conditions. The methane emissions from manure management vary across cattle types, production system, and manure management system. Considering that in this study, the scenarios are raised under four levels of productivity (see section 3.3), we applied the Tier 1a approach of the IPCC 2019 to estimate CH_4 emissions from manure, see *Equation A-8* and *Equation A-9* (eq. 10.22 and eq. 10.22A of chapter 10 of (IPCC, 2019)).

$$CH_{4\,(mm)} = \left[\sum_{T,S,P} \left(N_{(T,P)} \cdot VS_{(T,P)} \cdot AWMS_{(T,S,P)} \cdot EF_{(T,S,P)}\right)/1000\right]$$ **Equation A-8**

Where,

$CH_{4\,(mm)}$ = CH_4 emissions from Manure Management, kg CH_4 yr^{-1}. $N_{T,P}$ = number of head of livestock species/category *T*, for productivity system P; $VS_{(T,P)}$ = annual average VS excretion per head of species/category *T*, for productivity system P, in kg VS animal^{-1} yr^{-1}. $AWMS_{T,S,P}$ = fraction of total annual VS for each livestock species/category *T* that is managed in manure management system *S* in the country, for productivity system P, dimensionless. $EF_{T,S,P}$ = emission factor for direct CH_4 emissions from manure management by animal species/category T, in manure management system *S*, for productivity system P, in g CH_4 kg VS^{-1}.

The VS excretion per head per cattle type and per production system is calculated according to *Equation A-9* (eq. 10.22A of IPCC 2019).

$$VS_{(T,P)} = \left(VS_{rate\ (T,P)} \cdot \frac{TAM_{T,P}}{1000}\right) \cdot 365$$ **Equation A-9**

Where,

$VS_{(T,P)}$ = annual average VS excretion per head of species/category *T*, for productivity system P, in kg VS animal^{-1} yr^{-1}. $VS_{rate\ (T,P)}$= default VS excretion rate, for productivity system P, kg VS (1000 kg animal mass)$^{-1}$ day^{-1}. $TAM_{T,P}$ = typical animal mass for livestock category *T*, for productivity system P, kg animal^{-1}.

d) Direct N_2O emissions from manure management

The direct N_2O emissions generated by manure in the system 'pasture, range, and paddock' are reported by IPCC, 2019 method in section 11.2 of Chapter 11, under the category 'N_2O Emissions from Managed Soils' (IPCC, 2019). For cattle production in all the scenarios, N_2O emissions are estimated using *Equation A-10* and *Equation A-11* (Eq. 11.5 of chapter 11 of IPCC, 2019) by Tier 1 approach.

$$N_2O - N_{PRP} = \left[\left(F_{PRP} \cdot EF_{3\ PRP}\right)\right] \cdot 44/28$$ **Equation A-10**

Where,

N_2O-N_{PRP} = annual direct N_2O–N emissions from urine and dung inputs to grazed soils, kg N_2O–N yr^{-1}. F_{PRP} = annual amount of urine and dung N deposited by cattle grazing on pasture, range and paddock, kg N yr^{-1}. EF_{3PRP} = emission factor for N_2O emissions from urine and dung N deposited by cattle grazing on pasture, range and paddock, kg N_2O–N (kg N input)$^{-1}$. 44/28 = Conversion of N_2O–N emissions to N_2O emissions for reporting purposes.

$$F_{PRP} = \sum_{T}\left[\left(N_T \cdot Nex_T\right) \cdot MS_{T,PRP}\right]$$ **Equation A-11**

Where,

F_{PRP} = annual amount of urine and dung N deposited by cattle grazing on pasture, range and paddock, kg N yr^{-1}. N_T = number of head of livestock species/category T. Nex_T = annual average N excretion per head of species/category T in kg N animal^{-1} yr^{-1}. $MS_{T,\ PRP}$ = fraction of total annual N excretion for each cattle category T that is deposited on pasture, range, and paddock.

- **Land-use changes (LUC)**

LUC were considered based on the current regional conditions of the available area within the agricultural frontier and analyzing the results of the land demand for the proposed scenarios. Therefore, since the reference and low scenarios project an increase in the land demand for agricultural production, the conversion of shrubland to cropland is required for food crops production. On the other hand, beef production conditions for these two scenarios correspond to extensive cattle production. Considering that this cattle production system leads to soil degradation (Silva-Parra, 2018) (Rodríguez Borray et al., 2019) (CIAT & CORMACARENA, 2017) and the use of more land to meet future needs, it was defined that beef production requires the conversion of shrubland to degraded pastures. For the medium and high scenarios, it is projected that the increase in land demand does not exceed the current land demand. Therefore, for food crop production, the conversion is from cropland to cropland. For beef production, it is estimated that the cattle production system improves then, the land conversion is from degraded pastures to managed savannas, where the improvement in pastures and the mixture with forages, legumes, and trees allows the improvement of carbon stock of the entire production system and it benefits animal welfare (Chará et al., 2019).

In Colombia, the areas suitable for agricultural, livestock, forestry, aquaculture, and fisheries production were delimited recently (UPRA, 2018a). Considering that delimitation, Table A-6 shows the land distribution we assumed for this study. The largest area to focus the land intensification should be the foothill-high plain since this area has the mayor available agricultural area (ha) of the region. To date, the flooded plain area has been devoted mostly to cattle production rather than crop production. Also, considering the flooded plain has a sensitive ecosystem that could be affected by large-scale production of crops (Rincón et al., 2014)(UPRA, 2018b). Then, we consider that in the flooded plain area the focus should be mostly on livestock production and only in some small areas produce annual crops.

Table A-6. Land distribution and land suitability in the Orinoquia region.

Characteristics	**Orinoquia region**					
Entire region area[a]	25.4 Mha					
Available agricultural area[b]	15.5 Mha					
Regional landscape	**Flooded plain**		**Foothill**		**High plain**	
	5.0 Mha		2.8 Mha		9.7 Mha	
Land suitability[c] within the agricultural frontier	Crops	Cattle	Crops	Cattle	Crops	Cattle
	+	+++	++	++	+++	++

[a] Area that covers the limits of four departments Arauca, Casanare, Meta, and Vichada (DANE, 2016b)

[b] Official data of the national government which corresponds to available land for agricultural production in the Orinoquia region, Also called Agricultural frontier (DANE, 2016b).

[c] According to the zoning of production areas within the agricultural frontier made by (UPRA, 2018a) (UPRA, 2018b), land suitability is classified as follow: **highly suitable** (+++) corresponds to land with the best physical, ecosystem and socio-economic conditions for crop or cattle production. **Moderately suitable** (++) is related to areas with moderate physical, ecosystem or socioeconomic limitations that require investment around the area for optimal production management. **Lowly suitable** (+) is related to areas with significant limitations (physical, ecosystem or socioeconomic), which require large investments or the development of new technologies for optimal production (UPRA, 2018a) (UPRA, 2018b).

C. Parameters for calculation of GHG emissions associated to energy crops

For determining the GHG emissions for energy crops, the following key characteristics of the energy crop production are needed: for sugarcane, it is assumed that its production is exclusive for bioethanol production, a ratoon cycle of 7 years is assumed (Mekonnen et al., 2018). Currently, oil palm plantations in Colombia are used to produce crude palm oil (CPO) for both food use and biodiesel (Fedepalma, 2019a). However, it is assumed all oil palm cultivated on surplus land is dedicated to biodiesel production. Input data (chemicals, water, fuel, and electricity) for biodiesel production is based on a previous study by (N. E. Ramirez-Contreras et al., 2020). For oil palm crop, a lifetime of 25 years is assumed (5 years of establishment, 20 years of full crop cover, 24 harvests of fresh fruit bunches-FFB per year). Note that byproducts of sugarcane and oil palm production are not accounted for this analysis. The lignocellulosic biomass assessed is acacia (*A. mangium*) which is assumed to be used to produce bioelectricity (combined heat and power - CHP). A rotation of 10 years and one harvest is assumed (MADR, 2019). Data and assumptions see Table A-7. *A. mangium is* one of the most prominent species given its rapid growth, its high adaptive capacity to different environments, the potential for recovery of degraded soils, and the possibility of generating rapid changes in the landscape (Caguasango, 2017) (Reyes M., Carmona G., & Fernández, 2018) (Martinez, 2018). This plant has a high tolerance to conditions of water stress (deficit or excess) and nutritional deficiency in soils. Thus, it can grow in tropical areas with low rainfall, high solar radiation and high temperatures (Reyes M. et al., 2018). The use of *A.mangium* from the Orinoquia region is estimated for traditional timber products (boards, wood pulp) and wood products for the chemical, cosmetic and food industry, energy, second generation biofuels, charcoal, charcoal briquettes and activated carbon (Hegde, Palanisamy, & Yi, 2013) (Younis et al., 2020). However, the greatest use is expected to produce electricity (Martinez, 2018).

Table A-7. Data and assumptions for emissions of energy crops. These crops only grow in surplus land from the medium and high scenarios of agricultural yield increase.

Input data			Scenarios by 2030	
			Medium	High
Crop yield ($t\ ha^{-1}\ yr^{-1}$) (wet basis)	Sugarcane [a]		84.3	85.4
	Oil palm [b]		16.6	18.4
	Acacia [c]		16.5	19.3
Fertilization [d] ($kg\ ha^{-1}$)	Sugarcane	N	48	49
		P	114	116
		K	116	118
	Oil palm	N	92	104
		P	28	32
		K	190	214
	Acacia	N	109	127
		P	99	116
		K	52	61
Diesel consumption [e] ($l\ t^{-1}$)	Sugarcane		3.38	3.27
	Oil palm		4.60	4.44
	Acacia		3.84	3.71

[a] Yield data from (Agronet, 2019) (DANE, 2019b). **Sugarcane** is expressed in tons of cane per hectare. Note sugarcane crop yield does not report great variation between scenarios because the data were taken from the only current crop in the region with information from 2013-2018. Where *medium* scenario corresponds to percentile 80 of the period data; and *high* scenario corresponds to percentile 95.

[b] Yield data from (Fedepalma, 2019c). **Oil palm** yield is expressed in terms of Fresh fruit bunches (FFB) per hectare. The yield increase follows the regional data for the period 2012-2018. Where *medium* scenario corresponds to percentile 80 of the period data; and *high* scenario corresponds to percentile 95.

[c] Yield data from (Mendham & White, 2019). Acacia is expressed in tons of wood per hectare.

[d] For all scenarios, fertilization data to each energy crop were calculated based on data from (IPNI, 2002). The use of nitrogen fertilizers has implications for GHG emissions as described in Appendix B.

[e] Diesel consumption for oil palm is based on data from (N. E. Ramirez-Contreras et al., 2020). Diesel consumption in sugarcane from (Tsiropoulos et al., 2014). Diesel consumption in acacia plantation is taken from a forest harvesting system working the traditional forestry tasks using chainsaw, winch, and walking tractor (Cerutti, Calvo, & Bruun, 2014).

D. Parameters for calculation of GHG emissions associated to bioenergy products

The emissions associated with the three bioenergy products are calculated (i.e., sugarcane-bioethanol, oil palm-biodiesel, and acacia wood-bioelectricity) (see Table A-8). For all cases, the cultivation stage, the conversion plant, and the bioenergy burning (combustion) stage (i.e., the process of converting biofuel to energy: heat, electricity, or mechanical energy) are included.

- For bioethanol, conversion plant includes cane transport, milling process, and ethanol plant (Mekonnen et al., 2018).
- For biodiesel, conversion plant includes palm oil mill, physical refining (refined, blanched, and deodorized); transesterification; esterification of the free fatty acid (FFA); BD purification; glycerin purification (USP), and methanol recovery (N. E. Ramirez-Contreras et al., 2020).
- For bioelectricity, conversion plant includes sawmill and pellet mill (Roder et al., 2015).

Table A-8. Data of emissions along the production process of sugarcane-ethanol, oil palm-biodiesel and acacia-bioelectricity production

Emissions	Unit	Bioethanol		Biodiesel		Electricity	
		M	H	M	H	M	H
Cultivation emissions [a]	$kg\ CO_2eq\ t^{-1}_{biofuel}$	-39.0	-143.0	-3,089.0	-3,207.4	.	.
	$kg\ CO_2eq\ MJ^{-1}_{electricity}$	.	.	.	.	-0.071	-0.084
Conversion plant	$kg\ CO_2eq\ t^{-1}_{biofuel}$	6.4[b]		145.5[c]		0.0114 [g]	

Combustion	g CO_2eq $MJ^{-1}_{biofuel}$	0.3[d]		0.3[d]		.	
	g CO_2eq $MJ^{-1}_{electricity}$	.		.		1.9[e]	
Fossil fuel comparator [f]	g CO_2eq $MJ^{-1}_{biofuel}$	94		94		.	
	g CO_2eq $MJ^{-1}_{electricity}$	.		.		183	
Total emissions	g CO_2eq $MJ^{-1}_{biofuel}$	-2.1	-6.0	-79.3	-82.5	.	.
	g CO_2eq $MJ^{-1}_{electricity}$	.	.	.	.	-68.9	-82.1

[a] Data from energy crop production in the *medium (M)* and *high (H)* scenarios of the present study

[b] Data from (Mekonnen et al., 2018).

[c] Data from (N. E. Ramirez-Contreras et al., 2020).

[d] Data calculated based on Tier 1, (IPCC, 2019). It includes CH_4 and N_2O emissions

[e] Data calculated based on Tier 1, (IPCC, 2019). It includes CH_4, N_2O, and biogenic CO_2 emissions.

[f] Data from (European Parliament, 2018).

[g] Data from (Roder et al., 2015).

Chapter 5

Integral analysis of environmental and economic performance of combined agricultural intensification & bioenergy production in the Orinoquia region

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Abstract

Agricultural intensification is a key strategy to help meet increasing demand for food and bioenergy. It has the potential to reduce direct and indirect land-use change (LUC) and associated environmental impacts while contributing to a favorable economic performance of the agriculture sector. We conduct an integral analysis of environmental and economic impacts of LUC from projected agricultural intensification and bioenergy production in the Orinoquia region in 2030. We compare three agricultural intensification scenarios (low, medium, high) and a reference scenario, which assumes a business-as-usual development of agricultural production. The results show that with current inefficient management or with only very little intensification between 26% and 93% of the existing natural vegetation areas will be converted to agricultural land to meet increasing food demand. This results in the loss of biodiversity by 53% and increased water consumption by 111%. In the medium and high scenarios, the intensification allows meeting increased food demand within current agricultural lands and even generating surplus land which can be used to produce bioenergy crops. This results in the reduction of biodiversity loss by 8 to 13% with medium and high levels of intensification compared to the situation in 2018. Also, a positive economic performance is observed, stemming primarily from intensification of cattle production and additional energy crop production. Despite increasing irrigation efficiency in more intensive production systems, the water demand for perennial crops and cattle production over the dry season increases significantly, thus sustainable management practices that target efficient water use are needed. Agricultural productivity improvements, particularly for cattle production, are crucial for reducing the pressure on natural areas from increasing demand for both food products and bioenergy. This implies targeted investments in the agricultural sector and integrated planning of land use. Our results showed that production intensification in the Orinoquia region is a mechanism that could reduce the pressure on natural land and its associated environmental and economic impacts.

5.1 Introduction

The Colombian national government has targeted a transition towards a more sustainable economy (DNP, 2018a). This transition includes production and use of biomass for energy such as biodiesel, bioethanol, and bioelectricity (Congreso de Colombia, 2014; DNP, 2018b) in order to reduce fossil fuel usage and contribute to mitigating greenhouse gas (GHG) emissions. Currently, biofuels correspond to 5% of the total national fuel consumption (i.e., biodiesel and bioethanol) (UPME, 2019). Bioelectricity comprises 1.3% of the total national electricity production and is mainly produced from sugarcane bagasse (MX, 2020). By 2050, the national energy plan projects an increase in renewable energy production (UPME, 2019), particularly bioelectricity (DNP and Enersinc, 2017; MADR, 2019). Different bioenergy crops are projected to contribute to cover this growing demand including oil palm, wood, and crop residues (UPME, 2019).

The Orinoquia region is considered to have the greatest future expansion area for agricultural production in Colombia and therefore also for bioenergy crop cultivation (UPRA, 2018a). However, besides increasing bioenergy demand, also food demand is expected to increase in the future. At the same time, the region also aims to conserve natural savannas (CIAT & CORMACARENA, 2017; Prüssmann et al., 2020). Considering the currently low agricultural yields of the region (CIAT & CORMACARENA, 2017), agricultural intensification could then be key to meeting the various land uses. It would allow reducing the impacts from direct land-use change (LUC) and minimizing the risk of indirect LUC (ILUC) and their associated environmental impacts, while contributing to better economic performance of the agricultural sector (Brinkman et al., 2018b; Dauber et al., 2012; Rockström et al., 2017).

In our previous study on the Orinoquia region (Ramirez-Contreras et al., 2021), we concluded that improvements of current agricultural productivity are possible to such an extent that surplus land can be generated especially when strong measures were applied to increase cattle productivity. This surplus land may be used for different purposes, including nature conservation, afforestation, and energy crop production. We focus here on biomass production for energy purposes given strong interest in bioenergy by the Colombian government. Using only surplus land for biomass production for energy makes sure the current amount of natural vegetation can be maintained and the impacts related to LUC minimized. We found that agricultural intensification and resulting use of surplus land for energy crops would allow production of biomass for bioenergy with reduced GHG emissions and a low risk of causing ILUC. However, intensification and increased bioenergy production have also raised concerns about other environmental impacts such as water depletion and biodiversity loss (Creutzig et al., 2015; European Commission, 2016; Mendes Souza et al., 2017; Pardo et al., 2015) while the economic performance of such strategies is poorly understood. Therefore, an integrated analysis of environmental and economic effects of combined agricultural intensification and bioenergy production is needed to better understand the effects and to identify key measures to avoid impacts related to biomass production in the future. Additionally, this type of integrated analysis facilitates the evaluation of several land use and bioenergy crop scenarios, which is crucial for a region like Orinoquia where an increasing land demand for food, bioenergy, and nature conservation is expected, and where strategies are needed that can reconcile these demands (CIAT & CORMACARENA, 2017; Prüssmann et al., 2020).

In the literature, there are already attempts at such an integrated analysis concerning impacts of bioenergy (Howells et al., 2013; Thrän et al., 2016; Vera et al., 2020; Wu et al., 2018), but most of them have focused only on prevention of (I)LUC and its related GHG emissions (Brinkman et al., 2018b; Castanheira et al., 2015; de Souza et al., 2019; Gerssen-Gondelach et al., 2017; Kadiyala et al., 2016; Ramirez-Contreras et al., 2021). Some studies have also focused on the analysis of bioenergy and its socio-economic impacts (Koengkan, 2018; Walter et al., 2011; Wang et al., 2014) and a few studies addressed the impacts of bioenergy production on biodiversity and water (Mekonnen et al., 2018;

Rincón et al., 2014). Analyses that address multiple environmental impacts and the economic performance at the same time are, however, scarce in general and non-existent for Colombia. Moreover, for the Orinoquia region of Colombia, such an integral impact analysis is particularly important in order to i) understand the multiple impacts that agricultural intensification and increased bioenergy crop production can have, including potential trade-offs across impact categories, and ii) identify optimal land use and management strategies (Creutzig et al., 2015).

This study thus aims to conduct an integral analysis of the environmental and economic performance of agricultural intensification and bioenergy production on resulting surplus land in 2030 of the Orinoquia region. The analysis is conducted for three levels of agricultural (cattle and food crops) intensification (i.e., low, medium, and high scenarios) and three types of energy crops (i.e., sugarcane, oil palm, or acacia) based on our earlier study (Ramirez-Contreras et al., 2021). The present study assesses the impacts on biodiversity, water, and economic performance. While various, detailed methods for determining the effects on biodiversity and water exist, we focus here on methods that have relatively low complexity and can be used with generic data such as the mean species abundance index, soil-water balance, and net present value. This is due to the limited availability of primary data in the region, while still aiming to provide an overview of impacts caused by LUC for different future scenarios for the Orinoquia region. The novelty of the work comes the development of integral analysis of agricultural and bioenergy production and its environmental and economic performance and its application to a case study.

5.2 Material and methods

We assess the impacts of change in land use and land cover (here simplify as LUC) from agricultural intensification and bioenergy production on biodiversity, water, and economic performance, applying LUC projections for the Orinoquia region in 2030 from a previous study (Ramirez-Contreras et al., 2021). This methodology is an explorative effort to validate an integral impact analysis for the whole region considering agricultural intensification and using surplus land, resulting from this intensification, for biomass production for energy purposes. We analyze the impacts of these combined changes in land use on species abundance, water, and economic feasibility (Figure 5) as described in the following sections. We aim for identifying and using methods that can provide an overview of selected impact categories for different future (2030) scenarios. Such cruder scenarios make very detailed impact analyses less suitable, while (spatially-)specific information for various parameters is not available for the case study region. Where relevant and possible given data availability, we differentiate between the main characteristics of three subregions, i.e., flooded plain, highplain, and foothill of the Orinoquia region (section 1A in Appendix describes the geography, economic activities, characteristics of climate and biodiversity, and the various subregions in more detail).

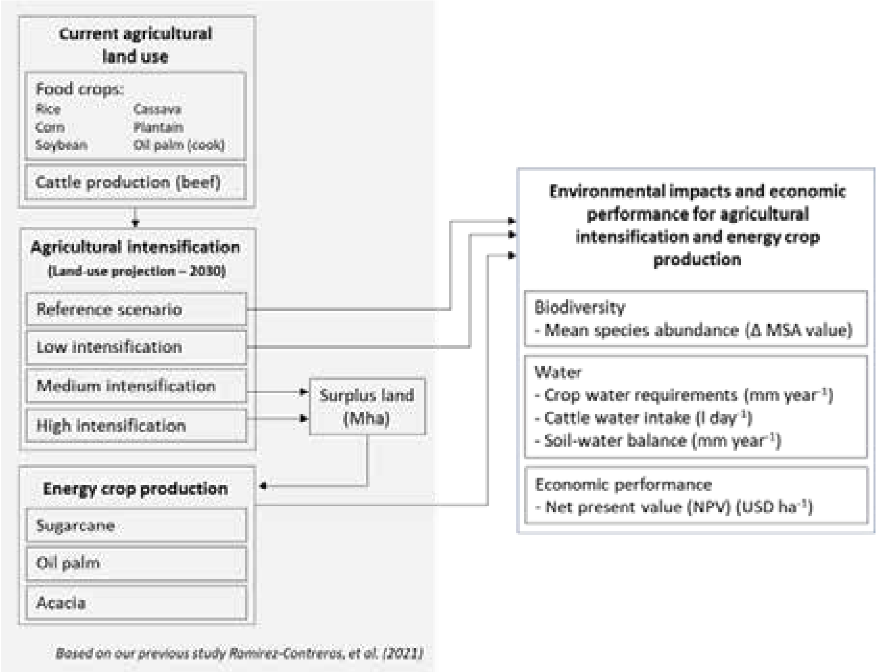

Figure 5. Overview of the environmental impacts and economic performance of agricultural intensification and energy crop production at subregional level. The light gray area is part of the analysis based on the results of our previous study (Ramirez-Contreras et al., 2021) where the LUC projections for the Orinoquia region in 2030 was obtained.

5.2.1 Land-use projections

Land-use projections for the Orinoquia region in 2030 are based on our previous study (Ramirez-Contreras et al., 2021) and consider the required increase in agricultural production to meet future food demand and developments in productivity. Land availability, population growth, food intake per capita, self-sufficiently ratio, and food losses associated with the production chain were analyzed. We consider that although, in theory, the area within the agricultural frontier of the Orinoquia region could be used for agricultural expansion to accommodate the projected increase in demand for agricultural products and for energy crops, it is necessary to maintain the natural vegetation of the region. Because the land within the agricultural frontier of the region is mainly natural vegetation, it is highly likely that the transformation of those areas to result in high LUC-related GHG emission and other negative environmental impacts. To increase agricultural production sustainably and produce low-ILUC-risk energy crops, agricultural intensification is required. Besides a reference scenario, in which a continuation of current agricultural practices was assumed, three agricultural intensification scenarios (low, medium, high) were included. Future demand in food crops and cattle production was projected with an increase of 3% per year for crops on average and 19% per year for cattle. The detailed descriptions of the management improvements and measures in agriculture and cattle production for the intensification scenarios are described in Ramirez-Contreras et al. (2021). Food crops included are rice, corn, soybeans, plantain, cassava, and oil palm. For the increase in cattle productivity, improved cattle management (fertilizing pastures and better-quality feed) was considered. Only the improvements made on cattle production resulted in surplus land for the medium (0.6 Mha) and high scenario (2.4 Mha) that were assumed to be used for energy crop production (i.e., sugarcane, oil palm, or acacia). The analyses focused on the potential of each individual energy crop per scenario, to enable comparison of the potential impacts between the crops (Ramirez-Contreras et al., 2021).

The projected land use (Table 6) is allocated to three subregions (flooded plain, highplain, foothills) based on the current land use pattern, which is in turn derived from the land cover map of IDEAM (2014). This map contains the most recent official land cover information of Colombia. It is assumed that the relative contribution of each subregion to the total cropland and pasture area remains stable until 2030. For example, according to IDEAM, 28% of the total cropland of the Orinoquia region was located in the highplain subregion. It is then assumed that in 2030, the same proportion of the total cropland is located in this subregion. The land cover map of IDEAM, comprising five land cover categories that were reclassified to three land-use classes by subregion, 1) cropland for food, 2) cattle grazing, and 3) natural vegetation (see Table A9 in Appendix). Natural forest and protected areas were excluded from the agricultural area of the region. Ideally, future projections of land use avoid converting the currently existing natural vegetation to another type of land use. However, in the reference and low scenarios analyzed by Ramirez-Contreras et al. (2021), the higher land demand to produce food (crops and beef) resulted in the conversion of natural vegetation to agricultural land.

Table 6. Current and projected land-use for 2030 in the Orinoquia region per scenario per subregion based on data from Ramirez-Contreras et al. (2021)

Subregions [a]	**Land-use type**	**2018 (Mha)**	**Projected land-use scenarios (Mha)**			
			Reference	**Low**	**Medium**	**High**
Highplain	Cropland (food)	0.15	0.47	0.44	0.26	0.23
	Pastureland (beef)	1.66	6.31	2.92	1.40	0.95
	Natural vegetation	5.37	0.40	3.83	5.37	5.37
	Energy crops [b]	n/a	n/a	n/a	0.16	0.63
Foothill	Cropland (food)	0.31	0.32	0.32	0.53	0.47
	Pastureland (beef)	3.65	3.90	3.72	3.07	2.10
	Natural vegetation	0.29	0.02	0.20	0.29	0.29
	Energy crops [b]	n/a	n/a	n/a	0.36	1.39
Flooded Plain	Cropland (food)	0.09	0.27	0.25	0.14	0.13
	Pastureland (beef)	0.93	3.58	1.64	0.78	0.53
	Natural vegetation	3.06	0.23	2.18	3.06	3.06
	Energy crops [b]	n/a	n/a	n/a	0.09	0.35

[a] Data for the Orinoquia region were assigned to the land-use projection by subregion per each scenario. For this, the information from the land cover map developed by IDEAM (2014) was used. More information in Appendix 2A.

[b] Energy crops are only planted in surplus land that comes from the agricultural intensification in the medium and high scenarios.

5.2.2 Biodiversity

Land-use changes by conversion from one type to another (such as natural vegetation to cropland) and by intensification affect biodiversity (Williams et al., 2020). Several indices to analyze biodiversity have been proposed in the literature such as Biodiversity Intactness Index (Scholes and Biggs, 2005), Wildlife Picture Index (O'Brien and Kinnaird, 2013), Human Footprint Index (Venter et al., 2016), Ecosystem Integrity (Blumetto et al., 2019), and the Forest Health Index (Grantham et al., 2020) among others. We are aware of the limitation of these indices but due to the lack of more precise data from the region, we chose the mean species abundance (MSA) index as an approximation to account for biodiversity change for this study.

MSA index uses an arithmetic mean of species abundances calculated in relation to six anthropogenic pressures and compare it to an undisturbed condition (Alkemade et al., 2009; Schipper et al., 2019). It is suggested to be a simple but practical indicator of biodiversity change. While a precise quantification of the MSA indicator requires data of original species abundance in a given area in both undisturbed and disturbed habitats (Schipper et al., 2019), the approach also provides default values which are based on studies and databases on species composition at global scale reported by GLOBIO model (Schipper et al., 2016). To assess the impact of land use by agriculture and energy crops on biodiversity, our study assesses the MSA_{LU} relationship (see Table A10 in the Appendix). The MSA_{LU} values range between 0 and 1 (0 refers to areas where the original biodiversity has disappeared and 1 refers to pristine areas (Schipper et al., 2016). The impact for each subregion is calculated by first multiplying the MSA_{LU} value by the area of each land-use category per scenario. Then, the sum of the MSA of food crops, pastures, natural vegetation, and when applicable also energy crops is divided by the total area of the subregion as shown in equation (5). We then calculated the net MSA change by comparing the intensification scenario to the reference scenario.

$$MSA_{LU} = \frac{\sum_{1}^{n}(MSA_x * A_x)}{\sum_{1}^{n} A_x} \qquad (5)$$

Where, MSA_{LU} = MSA corresponding with pressure of land use on the species abundance (dimensionless); MSA_x = MSA values of land-use categories (dimensionless); A_x = Surface area by land-use category (ha); x = land-use categories/type as defined in Table 6.

5.2.3 Water

To assess water resources, there are different types of water balances e.g., climatic, agroclimatic, hydrological, agroforestry, watersheds, among others (Cleves et al., 2016; IDEAM, 2019). Also, some simulation models such as CropWat (FAO, 2020) and AquaCrop allow the implementation of an agroclimatic alert system to support decision-making on alternative management technologies aimed at reducing the effects of adverse weather events (Cleves et al., 2016). More robust models such as the soil and water assessment tool (SWAT) require high-quality input data to predict both the long-term impacts at the basin scale and the environmental impact of land use, soil erosion control, and non-point source pollution control (Bieger et al., 2017). For this study, we selected the soil-water balance based on the FAO Penman-Monteith equation and the regional soil conditions since this is one of the most recommended methods (Allen et al., 2006; Cleves et al., 2016). With this approach, we can establish the soil water storage capacity by combining the projected land use by subregion and scenarios, and meteorological data as described below. To cover the crops' water deficit, we also calculated the irrigation water requirements (IWR) of perennial crops during the dry season (both food and energy crops) – annual food crops are only rainfed and therefore not considered. To assess water for cattle production, the amount of water intake (WI) is estimated by scenario and subregion.

Soil-water balance

The soil has a capacity to retain or store water, the level of which varies depending on the soil texture. Soil increases the moisture content when a precipitation event occurs or when irrigation water is applied (USDA-NRCS, 1993). Soil moisture losses are mainly due to the water that the plant transpires and the losses due to evaporation from the soil surface (i.e., evapotranspiration) (Alvarez et al., 2006). The soil-water balance makes it possible to compare the gains and losses of soil moisture during a given period of time. The soil-water balance calculation is based on the estimation of the evapotranspiration (ET), effective precipitation (EP), and the available water holding capacity of the soil over the year, following equation (6). Considering that crop water requirements are highly dependent on soil conditions (IDEAM, 2019), we first identify the predominant soil texture type for each subregion considering the information from the land cover map (IDEAM, 2014), soil classification map (IGAC, 2017), Rincón et al. (2014), and USDA-NRCS (2004a) (see Appendix 4.1A). Then, the available water holding capacity in these soils was estimated considering the methodology by USDA-NRCS (2004a) (*Equation A-15* and *Table A15* in Appendix).

$$WB_x = \sum_{i=1}^{12} (EP_i - ETc \pm \Delta d) \qquad (6)$$

$$ET_c = \left(ET_{0i} * Kc_{i,x}\right)$$

Where, WBx = Water balance for land cover type x (mm month^{-1}); EP = average effective precipitation month i (mm month^{-1}); ET$_c$ = crop evapotranspiration (mm day^{-1}); Δd = the variation in the soil moisture storage; ET$_{0i}$ = reference evapotranspiration of month i (mm month^{-1}); Kc$_{i,x}$ = crop evapotranspiration coefficient by specific growth stage in month i for land cover type x (factor); i = month January to December.

The EP was calculated by subregions according to *Equation A-12* in Appendix. Not all the precipitation that falls in a rain event infiltrates the soil, but a fraction is used by plants (i.e., effective precipitation) and another part is runoff (USDA-NRCS, 2004b). The soil-water balance uses effective precipitation for the calculation. This calculation is based on the monthly average precipitation for each subregion obtained through the Thiessen polygon method reported by USDA-NRCS (2004b) (see Figure A-2 in Appendix). Data of monthly average precipitation (Table A11 in Appendix) is taken from the Institute of Hydrology, Meteorology, and Environmental Studies of Colombia (IDEAM, 2020) for the period 1999-2019 from 132 meteorological stations located within the Orinoquia region (see Appendix 4A).

The reference crop evapotranspiration rate (ET$_0$) was calculated per month as an average for the entire Orinoquia region and not by subregion as not all needed data was available by subregion. The FAO Penman-Monteith method described by Allen et al. (2006) was used to calculate ET$_0$ considering meteorological data, i.e., temperature, wind speed, solar radiation, and humidity (see Table A12, Table A13 in Appendix). The crop evapotranspiration (ET$_c$) for specific plant material is calculated by multiplying ET$_0$ by the crop coefficient (Kc) (equation (6)). The Kc values were taken from Allen et al. (2006) assuming the Kc value of the medium crop development stage as shown in Table A14 in Appendix. The methodology was applied to six food crops (rice, corn, soybeans, plantain, cassava, and oil palm), three energy crops (sugarcane, oil palm, and acacia), and cattle pastures. ET$_c$ is thus first calculated per crop type using equation (6). Then a weighted average of ET$_c$ for all crops based on the land area of each crop is determined.

Crop irrigation requirements

For the dry season, the application of irrigation water to cover the water deficit was considered only for perennial crops (i.e., plantain, cassava, sugarcane, acacia, and oil palm) because the annual crops in the region are rainfed (i.e., rice, corn, soybean) (IDEAM, 2019). Moreover, the region has an inefficient use of water added to the possible variation in the seasonality of rains due to climate change (CIAT & CORMACARENA, 2017). Based on the result of the crop water need (ET$_c$) and the projected land-use area per scenario by subregion, the total irrigation water requirement is calculated according to *Equation A-16* and *Equation A-17* in Appendix. Irrigation water supply is affected by the efficiency of the irrigation system (USDA-NRCS, 1993). Therefore, according to the efficiency of the irrigation systems, we assume an irrigation efficiency for each scenario as shown in Table A16 in Appendix. Crop water requirements were first determined on a monthly basis as defined above. To show the annual impacts, they are then aggregated for annual values of crop evapotranspiration, effective precipitation, available water capacity that the soil can store, and water deficit.

Cattle water intake

For cattle production, the amount of water intake (WI) is estimated by scenario and subregion. Cattle water intake is calculated as proposed by Zanetti et al. (2019) (equation (**7**). This method allows predicting the WI by beef cattle in tropical conditions considering climatic variables, type of diet, and bodyweight of the animal (Zanetti et al., 2019). Then, water intake was calculated considering animal population, metabolic body weight (MBW), and dry matter intake (DMI). In addition, relative humidity and maximum temperature are part of the calculation (see input data in Table A17 in Appendix). The data for cattle land-use projection were taken from Table 6. Water requirement to produce cattle feed (pastures and forage sorghum) is assessed as defined above for crops. Note that, forage sorghum is considered only in the medium and high scenarios as a cattle feed. Both forage sorghum and pastures (i.e., improved pastures, native pastures, silvopastoral systems) are considered rainfed.

$$WI = 9.449 + 0.190 * MBW + 0.271 * \ T_{max} \ - 0.259 * HU + 0.489 * DMI \quad (7)$$

Where, WI = water intake (kg day^{-1}); MBW = metabolic body weight or live weight in kg$^{0.75}$ (0.75 is an exponent which considers the necessary diet of an animal to meet the maintenance and growth requirements to provide a weight gain of 0.75 kg/day); T_{max} = maximum temperature (°C); HU = relative humidity (%); DMI = dry matter intake (kg day^{-1}).

5.2.4 Economic performance

For analyzing the economic feasibility, the most widely used method is the net present value (NPV) which is usually used for assessing the economic feasibility of individual alternatives or to compare among different alternatives to choose the one that brings the largest benefits (Carvajal et al., 2019; Dale et al., 2013; Ramirez-Contreras et al., 2020; van Eijck and Faaij, 2014). Although the NPV makes it possible to determine the viability of an investment, complementary studies are required to reduce the risk associated with a financial investment given the uncertainty of the potential income (Gaspars-Wieloch, 2019; Thomas et al., 2018). Indicators such as net income per ha, internal rate of return, and return on investment, land use competition, and macroeconomic indicators can improve the identification of the viability of an agricultural investment (Dale et al., 2013; van Eijck and Faaij, 2014). Some economic models allow the analysis of economic links at the regional or national level, such as input-output analysis (Brinkman et al., 2018a) but this type of analysis requires a detailed input-output table not available for the Orinoquia region. Additional socio-economic indicators that could complement the socio-economic assessment of sustainable bioenergy production are related to the impact on the food security, employment, household income, and livelihood and equity impacts of the population in areas where energy crops are produced (Dale et al., 2013; Hunsberger et al., 2014; Ramirez-Contreras and Faaij, 2018).

Our study aims at an integral assessment of the impacts of agricultural intensification and resulting biomass production for energy on surplus land for the whole Orinoquia region. Therefore, the economic performance is determined by an NPV analysis at regional scale, where we compare different intensification levels and their implications (e.g., when there is intensification, more and other crops can be grown on the same amount of land). The regional net present value is used as an approximation of the regional value-added derived from the agricultural alternatives subject to different intensification scenarios. Even though we recognize our approach does not match exactly with that economic outcome, we consider agricultural intensification as an investment portfolio at a regional scale and use the regional NPV aggregation because it preserves the relative feasibility of each intensification level and its implications.

The NPV is the result of the summation of the initial investment (period 0) and the projected future monetary flows (income after expenses is net income) at each period, transferred to the present using a discount rate as shown in equation (8. The NPV measures here the profitability of the change in agricultural land use, including intensification and bioenergy crop production. A positive value of the NPV indicates the evaluated project may provide a greater financial return in the long term compared to the financial resources invested (i.e., a feasible investment), as opposed to a negative value of the

NPV which indicates that a project may not be cost-efficient (i.e., not feasible) (Sapag and Sapag, 2008).

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+i)^t} \qquad \textbf{(8)}$$

Where, NPV = Net present value per crop or cattle (USD ha^{-1}); R_t = net income at time t; i = discount rate (%); t = time of the cash flow; n = year planning horizon.

For this study, the NPV is first calculated at a hectare level for each individual agricultural activity (i.e., food crops, energy crops, and cattle production) at three different levels of intensification (low, medium, and high). Then, the regional NPV is aggregated by multiplying the individual NPV times the land area required for the considered crops and cattle (according to the intensification level) for the entire Orinoquia region. A discount rate of 5% is assumed for all productive projects, so we could compare them in financial terms. In this case we assumed that every alternative is compared to the safest possible investment, which in the Colombian case is the rate paid to term deposits (DTF) and has fluctuated around 5% during the past five years (Banco de la Republica, 2021a). We also consider inflation since our data is expressed in real terms. Given perennial crops (i.e., oil palm and Acacia) are included, the expected length of an oil palm project (25 years) is used to define the time span for the analysis. The NPV is complemented with the internal rate of return (IRR), which may be understood as the minimum rate at which financial resources invested in a productive project would meet investor´s expectations (Sapag and Sapag, 2008).

For cattle production, the capital expenditure (capex) is mostly represented by the purchase of bovines. The operational expenditure (opex) is represented by land rent (opportunity costs), animal health, labor, fencing, and pasture and forage management (i.e., soil preparation, fertilization, and grass/forage seeds costs). Note that for the low intensification scenario there is no investment in pastures nor forage as these activities are not implemented (Table A21 in Appendix). The operational costs consider land rent, technical assistance, labor, and animal handling and health (i.e., salts and vaccines). Live weight prices of beef cattle (USD kg^{-1}) and yields per hectare are used to compute the cash flow for the cattle alternatives. Considering that 85% of cattle production is carried out in the highlands and foothills and that for these two subregions cattle production behaves similarly, we assume these conditions for the entire region. Also, the foothills subregion usually is used for cattle-fattening with better performance or higher yields. Data are lacking to distinguish production costs at flooded plains, which might be of great importance in future research on this topic (Corrales and Nieto, 2017; Peñuela et al., 2014).

For all crops production, the capital expenditure includes soil preparation (chemical and physical), seeds, and sowing; while operational expenditure includes land opportunity costs, fertilization (inputs and application), pesticides, labor, technical assistance, and machinery rent. The expected cash flows (i.e., cash revenues) consider the sale price of raw materials for all crops in US dollar per ton (USD t^{-1}). See all input data in Table A19 in Appendix. For cattle and crops production, empirical data such as capex, opex, and revenues were estimated based on the information from the model developed for the Orinoquia region by Fontanilla-Díaz et al. (2021). Additional information collected is also shown in Appendix 5A.

5.3 Results

It was found that as the yields of agricultural production intensify, less or no conversion of natural vegetation areas to agricultural production is needed (see Figure 6). For example, in the high scenario of both the highplain and flooded plain subregion, the largest area corresponds to natural vegetation, compared to the reference scenario where the largest area corresponds to pastures for beef production in cattle extensive system. Also, in the medium and high scenarios, the production of energy crops is possible within the same agricultural area that was used in 2018 for cattle production (Ramirez-Contreras et al., 2021).

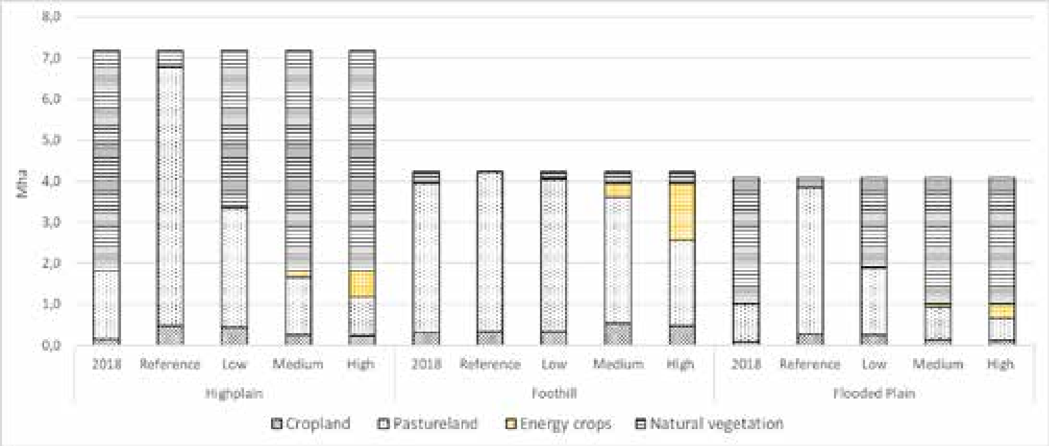

Figure 6. Projected land use and distribution by type of land use for three subregions and different scenarios in 2030 compared to 2018.

5.3.1 Biodiversity

For all subregions, the reference scenario results in a serious negative change in MSA, since about 92% of the current land under natural vegetation is converted to agricultural land to produce food crops and beef (Figure 7). This shows how important it is to improve agricultural management. When intensification is considered, an increase in the MSA value score is observed, the value for the medium (0.8) and high scenario (0.8) being higher compared to the reference scenario (0.3). This is mainly due to i) conserving biodiversity in natural vegetation combined with ii) reducing the impact of increased cattle production in terms of land conversion.

One result stands out when comparing the medium and high scenarios, since the medium scenario performs slightly better in terms of species abundance than the high scenario. This is because the conversion of cattle pastures to energy crop reduces the species abundance since pastureland has a better MSA value than energy crops (see Table A10 in Appendix). In the high scenario more pastureland is converted to energy crops than in the medium scenario. Thus, as land for energy crops is increased and land for intensive cattle decreases from the medium to the high scenario, biodiversity is negatively affected. However, it is important to note that these outcomes heavily depend on the MSA values assumed for different crops and land uses (see also the Discussion section).

At the subregional level, the MSA and the net change in MSA do not result in a significant difference between the highlands and the flooded plain, but in the foothill subregion a lower impact on the species abundance compared to the other two subregions is observed. This lower impact can be explained by the relatively small change in the areas of natural vegetation since the foothill has the highest share of agricultural land use at this time and therefore has the least area of natural vegetation to be converted (see also Figure 6).

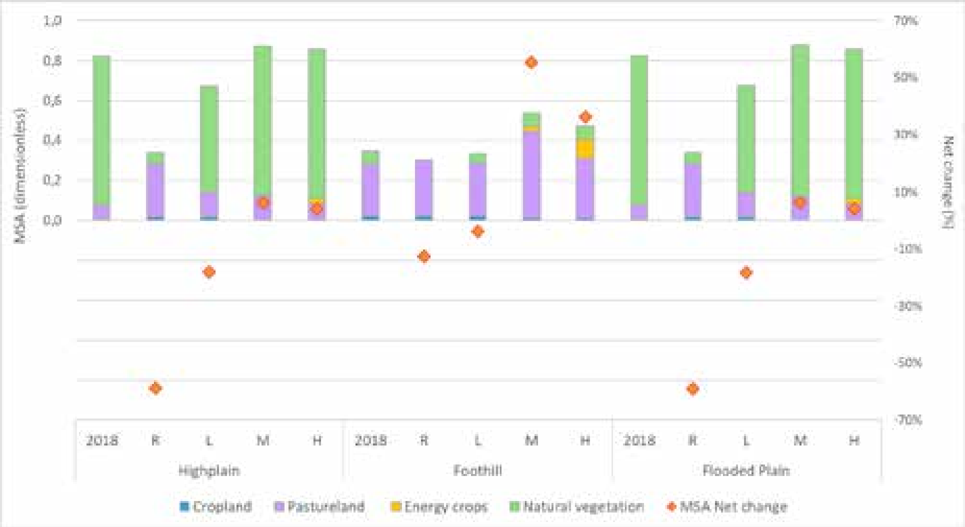

Figure 7. Total MSA by subregion and scenarios. The net MSA change is the percentage of change of the MSA values of the reference (R) and intensification scenarios (L - low, M - medium, H - high) with respect to 2018. For the medium and high scenarios, no distinction between the energy crops is made because the assigned MSA_{LU} value is the same for all (see Table A10 in Appendix).

5.3.2 Water

Crop water requirements

For all subregions, the weighted average evapotranspiration of all crops (ET_c; yellow dots) shows that, as crop yields intensify across scenarios, there is a reduction in water loss by evapotranspiration (see Figure 8). This is related to the reduction of crop areas caused by the improvement in crop productivity in the intensification scenarios. The available water (light blue bars) shows the amount of water in the soil that is available for use by plants per subregion per scenario. The monthly values (see Figure A-3 in Appendix) show that in the rainy season the water retention capacity in the soils is greater than during the dry season. For the three subregions, the dry season occurs between December and April and the rainy season occurs between May and November. For the rainy season precipitation is greater than evapotranspiration and thus supplying enough to full fill crop water requirements and therefore, no supplementary irrigation is required.

The water deficit (red bars) is greater in the reference scenario compared to the intensification scenarios. A high water deficit is associated with low crop yields due to the limitation of water that occurs in the dry season. This generates the need to apply irrigation water to minimize crop loss. As crop yields intensify, crops demand less water per unit of output. This allows a greater water storage or water availability in the soils and therefore less irrigation water is required. In the flooded plain, less water availability and greater water deficit are reported compared to the other two subregions. This is the result of a lower water retention capacity of the subregion's soils and lower effective precipitation.

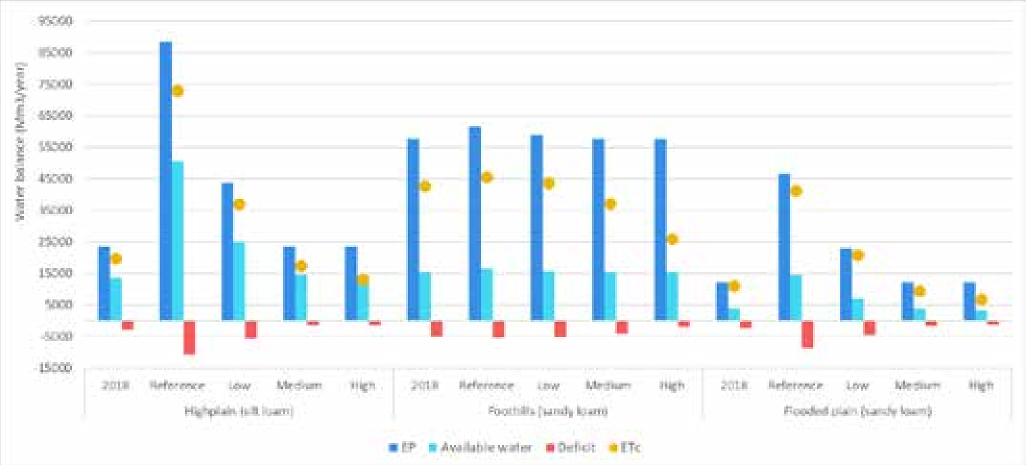

Figure 8. Annual soil-water balance for all crops by scenario and subregion. EP = effective precipitation (i.e., the fraction of the total precipitation that is actually used by crops to satisfy water needs; for each subregion, EP is related to the agricultural area by scenario to show the annual value used by crops); Available water capacity = the amount of water that a soil can store that is available for use by plants; Deficit = the amount of water needed in months when demand exceeds supply; ET_c = crop evapotranspiration (average for all crops grown in the subregion weighted by crop area). Note that the ET_c value for 2018, reference, and low scenario includes food crops and pastures. The medium and high scenarios include the food crops, pastures, and only the ET_c for acacia as an example of an energy crop. ET_c value of acacia is between the values for sugarcane and oil palm.

Regional needs for supplementary irrigation water for perennial crops for both food and energy over the dry season are presented in Table 7. For all cases, irrigation water requirement is higher than the water deficit as it takes the efficiency losses of the irrigation system into account (see Table A16 in Appendix). There are greater irrigation requirements for food crops in the reference and low scenario than for the medium and high scenario even though in the medium and high scenarios there are additional irrigation water requirements from energy crop production. This is due to increase water use and irrigation efficiency in the medium and high scenarios. For the energy crops planted on the surplus land of the medium and high scenarios, sugarcane reports the highest consumption of irrigation water as shown in Table 7 which is related to the crop's high transpiration rate.

It is important to note that in the high scenario more irrigation water for energy crops is needed than in the medium scenario (Table 7). This is due to the greater amount of surplus land available for perennial energy crops in the high scenario (2.4 Mha) than in the medium scenario (0.6 Mha). Thus, although irrigation water requirement per unit biomass production in the high scenario are lower than in the medium scenario, in absolute terms, more irrigation water is required.

Moreover, since the irrigation water requirements are affected by the efficiency of the irrigation systems assumed in the scenarios (Table A16 in Appendix), both the current situation and the reference and low scenarios assume the lowest efficiency of the irrigation system (30%). Therefore, a greater volume of water is required to supply the water deficits. For the medium and high scenario, the consumption of irrigation water decreases compared to the reference scenario since the efficiency of the irrigation systems is improved (50% and 80% for the medium and high scenarios, respectively). As more efficient irrigation systems are used, the volume of irrigation water can be reduced, thus the agricultural water demand would decrease. Compared to the reference scenario, agricultural intensification and efficient use of water reduces irrigation water for perennial food crops by 1% in the low scenario, 52% in the medium scenario, and 73% in the high scenario.

Table 7. Annual water deficit and irrigation water requirements (IWR) for perennial crops over the dry season, million m^3 year^{-1}, by scenario and subregion.

Scenario	Land-cover	Highplain		Foothills		Flooded plain	
		Deficit [b]	IWR [c]	Deficit [b]	IWR [c]	Deficit [b]	IWR [c]
2018	Food-crop [a]	175	835	294	1,255	136	554
Reference	Food-crop [a]	534	2,539	310	1,324	421	1,724
Low	Food-crop [a]	494	2,352	308	1,316	393	1,856
Medium	Food-crop [a]	228	825	505	1,294	216	551
	Oil palm [d]	258	942	608	1,567	253	645
	Sugarcane [d]	508	1,756	1,198	2,938	436	1,117
	Acacia [d]	319	1,150	486	1,854	207	761
High	Food-crop [a]	258	461	448	717	224	307
	Oil palm [d]	1,307	2,289	2,364	3,807	1,158	1,567
	Sugarcane [d]	2,278	4,268	4,659	7,140	1,869	2,716
	Acacia [d]	1,543	2,794	1,888	4,506	977	1,849

[a] For all scenarios, food-crop refers only to perennial crops i.e., cassava, plantain, and oil palm (cooking oil).

[b] Note that the deficit value refers to the lack of water available in the soil for crops over the dry season.

[c] IWR is the amount of irrigation water needed for meeting the water deficit of perennial food and energy crops over the dry season. Water deficit corresponds to the amount of water needed in months when demand exceeds supply.

[d] For the medium and high scenarios, it is assumed that all surplus land generated from the intensification is used either for sugarcane, oil palm, or acacia.

Cattle water intake

Considering that the animal weight and dry matter intake increase in the intensification scenarios compared to the reference scenario, water consumption also increases to satisfy the needs and metabolic requirements of the animals (Zanetti et al., 2019). The estimated water intake per animal for the reference scenario was 18.4 kg water day^{-1}, while this was slightly higher for the low (19.6 kg water day^{-1}), medium (20.5 kg water day^{-1}), and high (22.6 kg water day^{-1}) scenarios. Note that the water intake estimate considers the maximum temperature and relative humidity of the Orinoquia (i.e., 27.9 ℃; HU 80.4%), therefore the water intake by cattle is increased to alleviate animal heat stress. In addition, a greater consumption of dry matter in the diet of animals requires greater consumption of water. By increasing the body weight of the animal per scenario, there is a greater dry matter intake and therefore, greater consumption of water. This is mirrored in the total cattle water intake by scenario by subregion (see Table A22 in Appendix).

For each subregion, cattle water intake (Table A22 in Appendix) and the area dedicated to cattle varies (Figure 6). A smaller area results in less water use, but more animals mean more water use. The highplain and the flooded plain regions increase the cattle area in the reference scenario by 3.8 times and the water intake by 3.2 times compared to the current situation. Intensifying cattle yields, both cattle area and water intake decrease from the low scenario to the high scenario for both subregions. In the foothills, the reference scenario increases cattle area by approximately 1.1 times compared to the current situation, but the cattle area does not greatly decrease in the intensification scenarios (Figure 6). Therefore, the number of animals is greater than for the other two subregions. This results in higher cattle water intake in the foothills region than in the highplain and the flooded plain regions. Note that in the medium scenario the foothills have a larger cattle area than in the high scenario. Therefore, cattle water intake is greater (36.5 Mm^3 year^{-1}) than in the high scenario (34.3 Mm^3 year^{-1}). Furthermore, water intake by the animals is quite small compared to the water consumption by crops, but indirectly, the animals consume grass/forage which also needs water to grow.

Total water requirements

According to IDEAM (2019), the net water supply of the Orinoquia region in 2016 was slightly lower than 400.000 Mm^3 of which 35% is used by agricultural water demand and 10% used by cattle demand. We estimate here that in the reference scenario there is a demand of 5,600 Mm^3 year^{-1} of irrigation water only for perennial food crops and approximately 60 Mm^3 of water intake by cattle. As intensification scenarios increase agricultural and cattle yields, the water demand for food crops decreases (Table 7). In the medium and high scenario, the consumption of irrigation water for energy crops increases the regional water demand. Despite this increase, the range of total water demand is between 5800 and 15600 Mm^3 per year, which is still much less than the regional net water supply. Thus, it is possible to meet the demand for agricultural water for perennial crops and cattle production in all scenarios. However, the water resources are not distributed evenly in time and space (IDEAM, 2019). Therefore, adequately locating agricultural production areas and water storage capacity are key to minimizing future negative effects (CIAT & CORMACARENA, 2017) on local water supplies and groundwater tables.

5.3.3 Economic performance

Agricultural intensification increases the yield of food crops and cattle and, as a result, their profitability (see Figure 9). Considering that income from increased yields can be overruled by high capital investments and input costs, the positive results of agricultural and cattle income for all scenarios are highlighted. The intensification generates surplus land that becomes available for biomass production for energy that have a larger NPV per hectare. Thus, the aggregated revenue of the region increases in the intensification scenarios that generate surplus land for biomass production.

The NPV of the reference scenario is between 5 to 7 times smaller than the NPV of the high scenario with any of the energy crops. Considering that in the reference scenario the use of agricultural land is inefficient, a greater extension of land is required to generate the projected quantities of food. Agricultural intensification increases output per hectare and allows for additional production, which increases revenue and NPV. In the medium and high intensification scenarios, a larger portion of agricultural land is available for energy crops production. In the medium scenario, food crops and cattle production report an NPV of USD 7 billion. Depending on the energy crop, an additional 0.76 to 2.43 billion USD from energy crop production could be generated. In the high scenario, an NPV of 14 billion USD is reported from agricultural production and between 3.5 and 12.6 billion USD from energy crop production, strongly increasing the net income of agricultural and bioenergy land use for the region. For energy crops, palm oil performs better than sugarcane and acacia crop, while the NPV of acacia is slightly higher than sugarcane (see Figure A-4 in Appendix). These results are also reflected in the IRR analysis, confirming profitability of energy crop production for the medium and high scenarios. The IRR of the high scenario reports higher profitability than the IRR of the medium scenario. The investment alternative in energy crops has an IRR between 14.6% and 16.9% in the medium scenario and an IRR between 16% and 18.7% in the high scenario.

The NPV of food crops, energy crops, and cattle production is positive for all scenarios considering a 25-year time span (see Figure A-4 in Appendix). The net present value of all food crops increases from the reference to the high scenario. In the reference scenario, rice is the crop that reports the highest NPV (2,853 USD ha^{-1}) compared to the rest of the food products. In the reference scenario, plantain crop reports the lowest NPV (260 USD ha^{-1}) that is related to the low crop yield per hectare and the high investment and production costs. Cattle production does not report major differences in the NPV for the reference, low, and medium intensification scenario. Only in the high intensification scenario does the NPV of cattle report a substantial increase (2,846 USD ha^{-1}) compared to reference scenario, indicating that the economic benefits would be greater in an intensive cattle production system than in an extensive cattle production system. Energy crops have comparable NPV's for sugarcane and acacia wood in both the medium and high scenarios, but the NPV of oil palm fresh fruit bunches is higher than the other two energy crops in both scenarios. Considering that oil palm reports the same costs (i.e., establishment, fertilizers, labor, harvest) in the cultivation stage both for its use as food and for its use as bioenergy, it is highlighted that the NPV of the medium and high scenario is above all other food crops and energy crops. Our NPV strongly depends on market price developments for crops and cattle, which come with considerable fluctuations and uncertainties. Additional information regarding NPV considering the market prices fluctuations is shown in Figure A5 in Appendix where it is highlighted that NPV of oil palm fruit and sugarcane are extremely sensitive to changes in market prices.

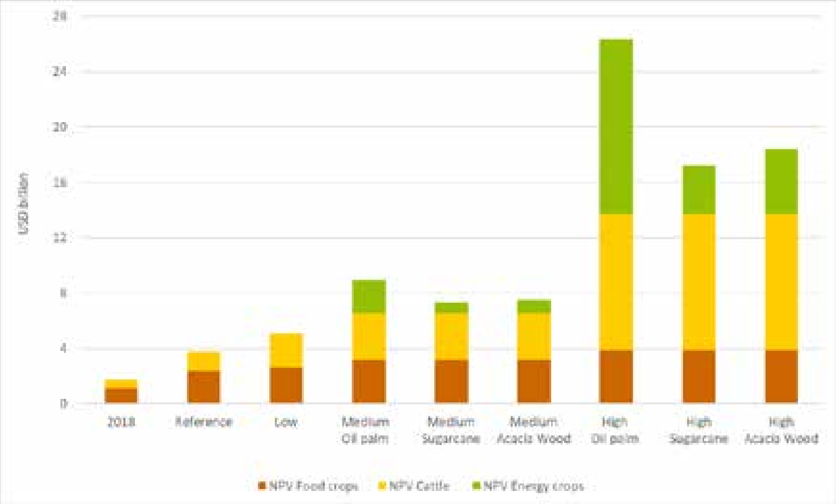

Figure 9. Regional net present value by scenario for food crops, cattle, and energy crops

5.3.4 Regional impacts of agricultural intensification & bioenergy production

The results for the whole region are summarized in Table 8, providing an overview of the changes by scenario compared to the situation in 2018. Besides impacts on biodiversity, water, and economic performance, we also include the results of our previous study on GHG emissions (Ramirez-Contreras et al., 2021). In the reference scenario, with a continuation of current inefficient management, 93% of the existing natural vegetation areas will be converted to agricultural land (see Figure 6). The resulting environmental impacts are clearly negative: GHG emissions increase by 64%, there is a 53% loss in species abundance, and the use of irrigation water for perennial food crops in the dry season increase by 111%. Despite the negative environmental impacts, the NPV for food crops and cattle report higher profitability compared to the current situation.

The low scenario performs better than the reference scenario in all impact categories because, with only small improvements in agricultural productivity, it is possible to strongly reduce the conversion of natural vegetation areas into agricultural land. Still, 29% of the current natural vegetation is converted to agricultural land. Environmental impacts are negative although lower than in the reference scenario. This is because the intensification pathway is not strong enough to compensate for the increased food demand. Therefore, there is no surplus land from the intensification that could be used for biomass production. The NPV of the (increased) agricultural production in the Orinoquia region increases to 191% compared to the current situation.

The medium and high scenarios perform better than the reference and low scenario because agricultural intensification allows creating surplus land for bioenergy crop production without the need of expanding into natural areas. As a result, there are net benefits in terms of the environmental impacts and economic performance of the agricultural sector, obtaining extra benefits from bioenergy in terms of GHG emission reduction and economic income for the Orinoquia region. The greatest contribution to reducing agricultural emissions in both scenarios comes from the intensified production of oil palm. The impacts of LUC on biodiversity result in an improvement of the total MSA value for the region by 8 to 13% for the medium and high scenarios, respectively, compared to the situation in 2018. In addition, energy crop production on surplus land does not result in a loss of biodiversity due to the protection of the current natural vegetation areas of the region.

The use of irrigation water for perennial food crops in the medium scenario increases 1% compared to 2018. In the high scenario, water use for food crops is reduced by 44% compared to the 2018 values. Thus, the high scenario performs better than the medium scenario since the irrigation system in the high scenario is more efficient than in the medium scenario reducing the water consumption. In addition to water use for food production, there is an increase in water demand for the three energy crops grown on surplus land. Here, the medium scenario reports less impact than the high scenario because the medium scenario has less surplus land for energy crop production and therefore fewer hectares per crop compared to the high scenario.

We found that intensification comes with increased profitability first in cattle production and second from the additional bioenergy crop production; only little changes occur in the NPV of agricultural crops production. Regarding increased profitability in cattle production, this finding is supported by the literature since intensified economic activities are found to be more resilient and profitable than their peers that are managed according to less efficient production patterns (González and Oliva, 2017; Thomas et al., 2018).

Table 8. Sustainability performance of agricultural intensification and bioenergy production by scenario in 2030 compared to 2018.

Performance indicators	**Orinoquia region**													
	Reference		**Low**		**Medium**					**High**				
	Net agricultural changes [a]		Net agricultural changes [a]		Net agricultural changes [a]		Net Bioenergy changes [b]			Net agricultural changes [a]		Net Bioenergy changes [b]		
							Op	Sc	Ac			Op	Sc	Ac
Land-use change [c] (change in natural vegetation)	--	-93%	-	-29%	+	0% (9% surplus land generated)	+	+	+	++	0% (35% surplus land generated)	++	++	++
GHG emissions [d]	--	+64%	-	+9%	++	-104%	++	+	+	++	-108%	++	+	+
Biodiversity [e] (change in species abundance)	--	-53%	-	-16%	+	+13%	+/-			+	+8%	+/-		
Water use [f]	--	+111%	--	+109%	+/-	+1%	-	-	-	+	-44%	--	--	--
NPV (revenue per hectare)	+	+116%	+	+191%	++	+276%	++	+	+	++	+687%	++	+	+

Signs: The signs indicate an increase (+) or decrease (-) of the value compared to 2018 where + positive change; ++ very positive change; - negative change; -- strong negative change; +/- negligible change

Abbreviations: Op - oil palm; Sc - sugarcane; Ac - acacia.

[a] Agricultural changes refers to the effects caused by food crops and cattle production.

[b] Bioenergy changes refer to the effects caused by energy crops production on surplus land from agricultural intensification. It is assumed that all surplus land is used either for oil palm, sugarcane, or acacia, causing the same impact since there is no variation in the hectares used for energy cultivation.

[c] Land-use changes are analyzed considering the cover type and agricultural area in 2018 conditions for the Orinoquia region, considering this year as the current situation according to our previous study (Ramirez-Contreras et al., 2021). The percentage of surplus land is the relationship between the total agricultural area currently in use in the Orinoquia region (6.8 Mha) and the surplus land obtained from the intensification of that agricultural land.

[d] GHG emissions are evaluated based on our previous study (Ramirez-Contreras et al., 2021).

[e] In the medium and high scenarios, agricultural intensification contribute to an increase in species abundance mainly due to reducing the impact of increased cattle production and conserving biodiversity in natural vegetation.

[f] Water use in agricultural production includes irrigation water for perennial food crops (i.e., plantain, cassava, oil palm for cooking oil) over the dry season. Moreover, it includes cattle water intake. In the medium and high scenario, water use for bioenergy considers irrigation during the dry season for the respective energy crops (i.e., oil palm, sugarcane, or acacia).

5.4 Discussion

Our analysis focused on the integrated analysis of the environmental and economic effects of agricultural intensification and bioenergy production. Although surplus land from agricultural intensification is considered available for any use (e.g., nature conservation, afforestation, food crops), its use for biomass for energy production is considered here as the Colombian government is promoting increased bioenergy use while sustainability concerns demand conservation of the current natural vegetation areas in the region. Moreover, producing energy crops at surplus land reduces the risk of (I)LUC related GHG emissions and other related impacts (de Souza et al., 2019; Gerssen-Gondelach et al., 2017). Although this study did not contemplate the use of spatially explicit analysis, official information was considered for land use by subregions where agricultural activities are carried out. In addition, the three subregions share similar characteristics in terms of land use, landscape, and agroclimatic conditions that allow an approximate vision of the impacts at the subregional level (CIAT & CORMACARENA, 2017; Rincón et al., 2014). The methods for this analysis were selected to allow for quick screening and assessment of future (and largely uncertain) developments in agricultural production for food and bioenergy and to accommodate limitations with respect to primary information and detailed data either for the subregions or the entire Orinoquia region. We discuss implications per impact category below.

5.4.1 Biodiversity impacts

Although the MSA approach allows providing a quick indicator of biodiversity change in the Orinoquia region, it also has important limitations. More precise quantification of the indicator requires data of original species abundance in a given area in both undisturbed and disturbed habitats (Schipper et al., 2019). For our study, it was not possible to obtain Orinoquia region-specific data on the species abundance. Hence, caution is advised if attempting to use MSA as an index of biodiversity change for the Orinoquia region as values do not represent its biodiversity status, but rather global values of species abundance per crop. For example, a shortcoming of the MSA approach is that in particular situations the mean of all species could be influenced by the hyperabundance of highly tolerant species (Pardo et al., 2019, 2018). This hinders the capacity of the index to serve as a "health check", since an increment in some species increases the mean species abundance but masks the potential negative ecological effect of that species. For example, Pardo et al. (2018) found that for the Orinoquia region the increase in oil palm triggers the relative abundance of crap-eating foxes.

Human-dominated landscapes are quite different in all regions as the historical process of LUC is the product of socio-economic history and geographic context (Garcia-Ulloa et al., 2012; Starik et al., 2020). Therefore, the relationships between species and land cover use would depend on the structure of the landscape and the intensity of each production system where agriculture is embedded (Cosentino et al., 2011; Franklin and Lindenmayer, 2009). Furthermore, the MSA values can partially be influenced by the vegetation patterns chosen (mixed cropping or agroforestry). For example, perennial crops such as oil palm have been shown to have slightly-to-substantially more diversity (species richness + species abundances) of some groups than pastures (Furumo and Mitchell Aide, 2019; Gilroy et al., 2015; Prescott et al., 2016). Therefore, using the same MSA value for pastures and perennial energy crops, as was done in this study, does not allow us to understand biodiversity effects at different land uses in the Orinoquia. Although the MSA provides a general index to rapidly assess a regional pattern in LUC, it does not completely cover the complex biodiversity concept (Alkemade et al., 2009). Then, the implementation of this index as a monitoring tool at local or even regional scales should include complementary indicators/metrics to capture properly the patterns of biodiversity loss in productive systems (Bakewell et al., 2012; Cipullo, 2016; Faith et al., 2008).

5.4.2 Water

Crop productivity is directly associated with the efficient use of water since the hydric deficit causes hydric stress affecting the response of the crop yield, while the presence of the required amount of water benefits crop yield (Steduto et al., 2012). For example, this consideration is being evaluated in the northern region of the country, where a study is being carried out on the impact of irrigation efficiency on oil palm productivity, through the adoption of more efficient water management technologies to reduce water use (Kaune et al., 2020). In our study, the soil-water balance provides a general idea to quantify the crop water needs and implement management measures that optimize the use of water in a crop production area. This method allows the equation to be simplified or made more complex depending on the available data (Cleves et al., 2016), but it has some limitations. Although the Orinoquia region has a considerable number of public weather stations for data such as precipitation, datasets are not complete since there is little or no updated report on variables such as solar radiation, wind speed, and relative humidity. Despite this, the method allows its use with limited climatic data (Cleves et al., 2016) even if the results will not be as accurate.

Advanced modeling methods can be applied to establish more specific interactions between climate, soil, crop genetics, and technical management of the area to optimize water use. The SWAT model can be used for sustainable water planning and management of watersheds (Nasiri et al., 2020). It is a reliable model in the analysis of hydrological processes applicable in various climatic environments and varied hydrological flows (Bieger et al., 2017; Nasiri et al., 2020). Results not only depend on the applied analysis method, but also on the quality of the information. The use of geographic information systems (GIS) and remotely sensed data offer more precise information to estimate e.g., the hydrological variables of a watershed (length, catchment area, average slope, CN number curve, etc.) (Grimaldos, 2013). Moreover, the impact of climate change on water resources was not taken into account in our study, although it may affect the results. Still, we consider this effect to be limited given the time frame of our analysis until 2030. Future studies could consider the effect of climate change, especially relevant for flooded savannas and the water balance of the sub-basins of the region.

5.4.3 Economic performance

NPV analysis in this study focused on the long-term net effect or profitability of agricultural intensification and using surplus land for bioenergy crop production. The management of sustainable agricultural and bioenergy production must also include the development of markets and trade, as well as financial facilities that allow increasing productivity (FAO, 2017). The carbon market has recently been developed for the purchase or sale of credits that represent the capture or avoided emission of one ton of carbon dioxide equivalent. Payment for environmental services related to reducing the soil degradation and soil carbon storage has also been developed. These mechanisms can contribute to financing projects for bioenergy production since they facilitate the voluntary compensation of GHG emissions e.g., through the purchase of carbon credits (Henry et al., 2017; Rudas et al., 2016). Intensified economic activities are found to be more resilient and profitable than their peers that are managed according to less efficient production patterns (González and Oliva, 2017; Thomas et al., 2018). Not-intensified production is likely to produce economic losses in low market price scenarios (Figure A5 in Appendix). Added to this, it is also important for farmers to advance in the adoption of sustainable management practices to increase both the health of crops and the economic benefits that a sustainable increase in yields can bring (Mosquera-Montoya et al., 2017; Ramirez-Contreras and Faaij, 2018).

5.5 Conclusions

This study focused on evaluating an integral analysis of environmental and economic impacts of LUC from projected agricultural intensification and bioenergy production in the Orinoquia region in 2030. If agricultural production continues with current inefficient management, 93% of the existing natural vegetation areas will be converted to agricultural land to meet the demand for food in a reference scenario for 2030. This results in more than a doubling of both GHG emissions and the losses of biodiversity, as well as an increase of over 100% in the consumption of irrigation water compared to 2018. Already with a small intensification of the current agricultural crop and cattle production, a notable reduction was found in the conversion of natural areas to agricultural land. However, the increased yields are not big enough to fully compensate increased food demand; food production would still require the conversion of 29% of natural areas. The impacts on biodiversity and water are negative although less than in the reference scenario. The medium and high intensification scenarios allow meeting the need for food within current agricultural lands and make surplus land available to produce bioenergy crops without converting natural areas. This results in the reduction of environmental impacts, particularly reducing GHG emissions and efficiently using irrigation water. In addition, the production of energy crops on surplus land does not imply a loss of biodiversity in the current areas of natural vegetation in the region. For all scenarios, a positive net present value, between 120% and 690%, is found for agricultural and bioenergy production in Orinoquia.

The results indicate that agricultural productivity improvements in the Orinoquia region are key to reduce the pressure on natural areas from increasing demand for both food products and bioenergy. Our analysis shows, it is possible to meet the demand for agricultural products and produce bioenergy without converting natural land. This requires targeted investments in the agricultural sector and particularly in the cattle production system given the surplus land comes from cattle intensification. Considering the findings, the Orinoquia region needs integrated planning of agriculture and bioenergy production, particularly land-use planning to distribute agricultural activities (i.e., crops and cattle) according to agroclimatic conditions, soil characteristics, and water supply to reduce potentially negative environmental impacts and maximize yields. This must consider the environmental offer, fauna and flora, water dynamics, and ecosystem services. At the same time, the region also aims to conserve natural savanna ecosystems, thus agricultural intensification creates the opportunity to maintain these areas without transformation, benefiting biodiversity and ecological processes.

However, it should be noted that the flooded plain subregion has restrictions for agriculture and cattle production intensification and is not suitable for energy crops given its agroclimatic particularity. Therefore, proper local planning of land use and intensification of agricultural areas must be carried out. Even, land-use zoning should exclude these areas from intensive agricultural production to minimize associated environmental risks. Moreover, it is important to highlight that the increase in agricultural and energy crop production as projected in our analysis results in greater pressure on water resources. To minimize this pressure, agricultural intensification requires the application of sustainable management practices to improve the efficiency of water productivity. This first explorative study is useful for identifying the potential impacts of land use on biodiversity, water, and net economic benefits in the region in general terms, but future research is needed, particularly including spatially specific assessments to illustrate variation within the subregions and assessing uncertainties.

Likewise, the country's public policies could support strategies to stimulate the development of activities in the agricultural sector that result in economic benefits, taxes reduction, or payment schemes for ecosystem services around water provision and flow regulation. This may include economic incentives for decarbonizing agricultural production, such as incentives for soil improvement, increased carbon stock, reduced chemical fertilization, and increased organic fertilization. Another government strategy can help provide greater support for research and development in the country's agricultural sectors. Additionally, the government can encourage the employment of personnel trained in management and improvement tasks for agricultural production.

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Appendix

1A. Study area

Orinoquia is one of the five ecoregions of Colombia, characterized by a diversity of ecosystems that includes for example natural savannas, gallery forests, flooded forests, estuaries, and wetlands (CIAT & CORMACARENA, 2017). The region has an area of 25 million hectares (Mha) (DANE, 2016) covering 22% of the total country area (Figure A-1). Most of the region has a tropical climate with an average temperature varying between 14 °C and 28 °C, rainfall varies between 1,000 and 7,000 mm/year, and the altitude ranges between 200 and 1200 meter above sea level (Romero-Ruiz et al., 2012). In much of the region the climate is monomodal with a period of rains and a very marked dry season (CIAT & CORMACARENA, 2017). Orinoquia region is one of the richest wildlife areas in wetlands and has the greatest diversity of birds and fish in the country (Romero-Ruiz et al., 2012). Also, the region has reported around 210 species of mammals, 100 species of amphibians, 170 species of reptiles, 52,700 species of insects, 4,800 species of fungi, 3,520 species of tropical trees, and 13,900 species of different kind of plants (CIAT & CORMACARENA, 2017). However, despite the great biodiversity of the region, it has been reported the main direct cause of biodiversity loss in the Orinoquia is land-use change (WWF-Colombia, 2017).

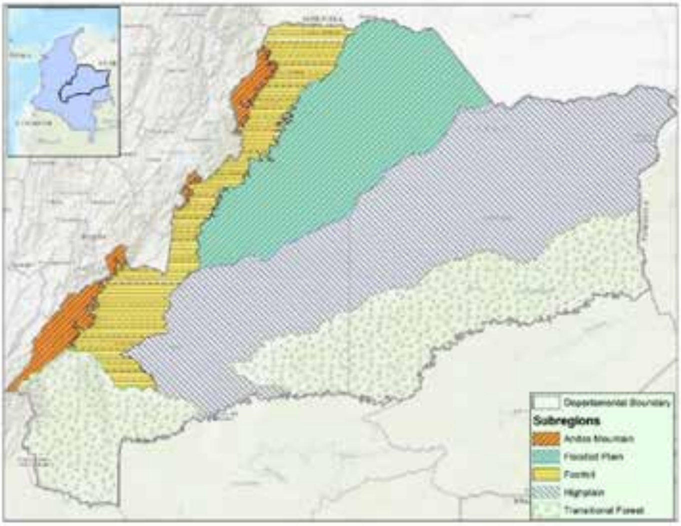


Figure A-1. Map of the Orinoquia Region with the division by biogeographic subregions within the Orinoco River basin. For the purposes of this study, the Orinoquia region comprises the departmental limits of Arauca, Casanare, Meta, and Vichada. Based on Rincón et al. (2014) and Prüssmann et al. (2020).

In the region, about 55% of the area is used for cattle grazing and 5% for crops production (CIAT & CORMACARENA, 2017). The economic sectors with the highest participation in water demand are crops (35%), hydropower (23%), and livestock (10%) (IDEAM, 2019). For crops production, about 90% of water requirement comes from rainfall (soil moisture) with the remaining 10% being met by irrigation (IDEAM, 2019). For livestock sector, cattle water demand constitutes 70% of the total consumption of the sector (IDEAM, 2019). In the region, both economic and demographic growth has generated excessive pressure on ecosystems and natural resources (CIAT and CRECE, 2018) making the region one of the most threatened ecosystems in the country (Romero-Ruiz et al., 2012). In the last decade, the region has had the highest average GDP growth among all regions from Colombia with an average annual growth rate of 5.4% (Delgado and Pérez, 2018). Agriculture, forestry, and other land use (AFOLU) sector contributed 10.3% to regional GDP (DANE, 2020; Delgado and Pérez, 2018). To reduce the impacts of agricultural development in the coming years, the region must align economic growth with the protection and conservation of biodiversity and water resources (CIAT & CORMACARENA, 2017).

Since the Orinoquia region has a diversity of landscapes, these have been classified into subregions that share similar characteristics (e.g., soil, ecosystems, land-cover, water sources) (Prüssmann et al., 2020; Rial et al., 2016). The three subregions that currently have agricultural land use are the flooded plains, high plains, and foothills. Much of the agricultural and economic development of the Orinoquia region has taken place in the foothill subregion, while the highplain and the flooded plain have been little intervened by the agricultural sector (CIAT & CORMACARENA, 2017). Currently, the flooded plain is the subregion most sensitive to changes in land use due to its high biodiversity values and high carbon stocks (Peñuela et al., 2019; Rincón et al., 2014). Despite this, in the flooded plain there are areas where small-scale crops and cattle production are developed. Some studies have highlighted that in the flooded plain, it is possible to continue using some areas that combine agricultural production with the preservation of ecological importance areas (Lowenberg-DeBoer et al., 2018; Peñuela et al., 2019). At the same time, other studies warn that land-use change in the flooded plain could have serious implications on biodiversity, water sources, productivity (decrease), and agricultural production costs (increase) (Etter and Zuluaga, 2017; Rincón et al., 2014).

2A. Parameters for calculation of land-use projection

The projected land use for 2030 is allocated to the three subregions based on the current land-use pattern, which is derived from the land cover map of IDEAM, (2014). We assume, the total land cover selected corresponds to 100%. Then, to each subregion is assigned the percentage of land cover according to the portion of the area in the region as shown in Table A9. It is assumed that the relative contribution of each subregion to the total cropland and pasture area remains stable until 2030. The land cover map of IDEAM, comprising five land cover categories according to the Corine Land Cover methodology adapted for Colombia: 1) artificial territories (cities, population centers); 2) agricultural territories (areas dedicated to annual and perennial crops, pasture areas, and heterogeneous agricultural areas); 3) forests and semi-natural areas (wooded, shrub, and herbaceous plant covers, bare soils, rocky, and sandy outcrops); 4) wet areas and 5) water surfaces (IDEAM, 2014). For this study, we reclassified those categories to three land-use classes by subregion: 1) Cropland (food), 2) Cattle grazing, 3) Natural vegetation.

Note that according to the land cover map of IDEAM, (2014) a total of 13.6 Mha were identified as land used for crops, cattle production, and natural areas. While according to UPRA, (2018b), the land available for agricultural purposes, also called *agricultural frontier*, corresponds to 15.5 Mha. It means, in this study, we are working with 15.5 Mha for the entire Orinoquia region, because this is the official area for agricultural expansion (MADR, 2018a).

Table A9. Area and proportion (%) of land cover for each subregion taken from the land cover map by IDEAM, (2014).

Subregion	Land cover categories	Area (ha)	%
Highplain	Cropland (annual and perennial crops)	97,625	0.7
	Pastureland (pasture and heterogeneous areas of pastures and crops	702,508	5.2
	Natural vegetation (herbaceous or shrubby)	6,540,665	48.1
Total Highplain area		**7,340,798**	**54.0**
Flooded plain	Cropland (annual and perennial crops)	53,775	0.4
	Pastureland (pasture and heterogeneous areas of pastures and crops	392,134	2.9

	Natural vegetation (herbaceous or shrubby)	3,727,440	27.4
Total Flooded plain area		**4,173,348**	**30.7**
Foothill	Cropland (annual and perennial crops)	193,503	1.4
	Pastureland (pasture and heterogeneous areas of pastures and crops	1,541,978	11.3
	Natural vegetation (herbaceous or shrubby)	347,255	2.6
Total Foothill area		**2,082,736**	**15.3**
Total Orinoquia area		**13,596,882**	**100**

3A. Parameters for calculating the biodiversity indicator MSA

Based on that MSA_{LU} values can be related to the intensity of agricultural land-use (cultivated and managed areas) (Schipper et al., 2016), we assume the assignment of MSA values considering the management practices applied to increase yields in each intensification scenario (Ramirez-Contreras et al., 2021) as shown in Table A10.

Table A10. Input data for MSA_{LU} value by scenario

Land use type	Scenario	MSA_{LU}
Natural vegetation	All scenarios	1.0
Cropland [a]	Reference/low	0.3
Cropland [c]	Medium/high	0.1
Pastureland [b]	Reference/low	0.3
Pastureland [d]	Medium/high	0.6
Sugarcane [e] / Oil palm [e] / Acacia [f]	Medium/high[g]	0.3

Data taken from Schipper et al. (2016) are:

[a] Assumed for cropland - minimal use or low input agriculture

[b] Assumed for pasture - man-made

[c] Assumed for cropland - intense use

[d] Assumed for pasture - intense use

[f] Acacia data is assumed from woody biofuels data

Data taken from van der Hilst et al. (2012) are:

[e] Sugarcane and oil palm data is assumed from perennial bioenergy crops data

[g] Sugarcane, palm oil, and acacia are only planned on surplus land in the medium and high scenario.

4A. Parameters for calculation of water use

4.1A Soil-water balance calculations for crops

Water use quantification is made for food-crops (rice, corn, oil palm, soybean) and for the energy crops (sugarcane, oil palm, and acacia) considering the soil texture by subregion described in Table A15.

Effective precipitation (EP) is largely determined by the available soil water storage (USDA-NRCS, 1993). EP is calculated by subregion using the *Equation A-12*. EP is based on the monthly average precipitation for the period 1999-2019 reported from 132 meteorological stations located within the limits of the Orinoquia region (i.e., Arauca, Meta, Vichada, and Casanare) and reported by IDEAM, (2020). Table A11 shows the average of monthly precipitation by subregion.

$$EP_i = \frac{MP(125-0.2*MP)}{125}, \text{ for MP < 250 mm}$$

Equation A-12

$$\boldsymbol{EP_i = 125 + 0.1 * MP}, \textbf{ for MP > 250 mm}$$

Where, EP = Effective precipitation in month *i* (mm month^{-1}). MP = monthly average rainfall (mm month^{-1}). i = month of the year from January to December.

Considering that precipitation varies in time and space according to the general pattern of atmospheric circulation and local factors, the spatial variability of precipitation for each subregion was determined following the Thiessen method (USDA-NRCS, 2004c) to obtain the distribution of the average monthly precipitation for each subregion. Figure A-2 shows the distribution of the Thiessen polygons to relate the mean precipitation reported by each meteorological station with the surrounding area. For this, the areas were delimited by subregion and then, those areas were interpolated with the monthly precipitation data reported by each meteorological station.

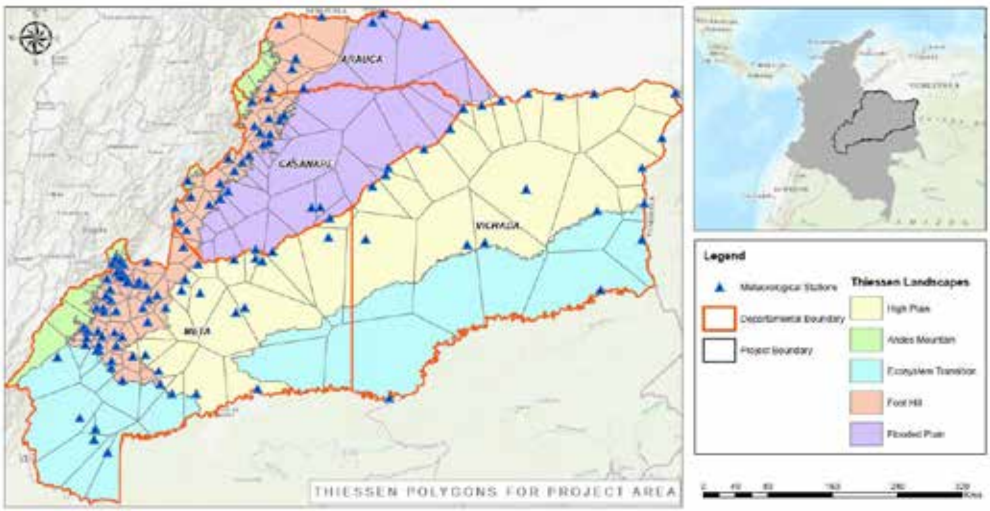


Figure A-2. Thiessen polygons maps where the weighted precipitation for each subregion was determined.

Table A11. Average of monthly precipitation and monthly effective precipitation (mm) by subregion

Month	**Highplain**		**Foothill**		**Flooded plain**	
	Monthly Precipitation (MP)	Effective precipitation (EP)	Monthly Precipitation (MP)	Effective precipitation (EP)	Monthly Precipitation (MP)	Effective precipitation (EP)
Jan	57.8	52.5	77.5	67.9	38.1	35.8
Feb	25.2	24.2	34.8	32.8	16.3	15.9
Mar	29.1	27.7	45.4	42.1	20.2	19.5
Apr	89.4	76.6	145.3	111.5	68.6	61.1
May	217.2	141.7	312.5	156.3	203.1	137.1
Jun	291.9	154.2	361.3	161.1	271.7	152.2
Jul	330.0	158.0	335.3	158.5	295.7	154.6
Aug	297.7	154.8	285.0	153.5	258.7	150.9
Sep	233.7	146.3	240.0	147.8	212.1	140.1
Oct	199.2	135.7	237.6	147.3	201.5	136.5
Nov	183.7	129.7	252.0	150.2	172.9	125.1
Dec	129.7	102.8	185.5	130.4	103.0	86.0

The **reference crop evapotranspiration rate** (ET_0) considers the effects of different weather conditions (Allen et al., 2006). ET_0 is calculating for the whole Orinoquia region using the FAO Penman-Monteith equation (*Equation A-13*). Meteorological data necessary for calculating ET_0 were taken from several stations located within the limits of the four departments that make up the Orinoquia region, being 35 stations for temperature, 4 stations for solar radiation, 12 stations for wind speed and 33 stations for relative humidity as shown in Table A12. The data correspond to the period 1999-2019 and are reported as monthly data by IDEAM, (2020).

Table A13 shows the additional regional information required to calculate the monthly ET_0 following the FAO guidelines for computing crop water requirements (Allen et al., 2006). Note that the values of constants/default are taken from the same document.

Equation A-13

$$ET_0 = \frac{0{,}408\,\Delta\,(R_n - G) + \gamma\,\frac{900}{T+273}u_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0{,}34\,u_2)}$$

Where, ET_0 = reference evapotranspiration (mm day^{-1}); R_n = net radiation at the crop surface (MJ m^{-2} day^{-1}); G = soil heat flux density (MJ m^{-2} day^{-1}); T = air temperature at 2 height (˚C); u_2 = wind speed at 2 height (m s^{-1}); e_s = saturation vapor pressure (kPa); e_a = actual vapor pressure (kPa); e_s - e_a = saturation vapor pressure deficit (kPa); Δ = slope vapor pressure curve (kPa ˚C^{-1}); γ = psychrometric constant (kPa ˚C^{-1}).

Table A12. Regional meteorological data for the calculation of ET_0 using the FAO Penman-Monteith equation.

Month	T_{max} (˚C)	T_{min} (˚C)	U_2 (windspeed) (m s^{-1})	RH_{mean} (%)
Jan	32.7	21.7	2.40	73.8
Feb	33.5	22.2	2.33	71.3
Mar	33.1	22.6	1.93	75.4
Apr	31.7	22.5	1.44	81.8
May	30.8	22.3	1.31	84.3
Jun	30.0	21.9	1.31	85.4
Jul	29.9	21.7	1.42	85.1
Aug	30.6	21.8	1.44	83.6
Sep	31.4	22.0	1.49	82.3
Oct	31.6	22.3	1.52	82.1
Nov	31.7	22.5	1.67	81.8
Dec	31.9	22.2	2.14	78.2

Table A13. Input data to regional level for the calculation of ET_0 using the FAO Penman-Monteith equation.

Parameter	Unit	Value
Altitude (regional average height)	m	288.6
Latitude (φ)		4°8'N
Regression constant (a_s)	dimensionless	0.25
Regression constant (b_s)	dimensionless	0.5
Crop reflection coefficient (α)	dimensionless	0.23
Stefan-Boltzmann constant (σ)	MJ k^{-4} m^{-2} dia^{-1}	4.90E-09
Psychrometric constant (γ)	kPa °C^{-1}	0.07
Specific heat under pressure (C_p)	MJ kg^{-1} °C^{-1}	1.01E-03
Atmospheric pressure (P)	kPa	99.4
Molecular weight ratio of water vapor/dry air (ε)	dimensionless	0.622
Latent heat of vaporization (λ)	MJ kg^{-1}	2.45
Elevation above sea level (z_)	m	300
Solar constant (G_{sc})	MJ m^{-2} min^{-1}	0.082

The **crop evapotranspiration rate** (ET_c) is described in *Equation A-14 w*here the reference evapotranspiration (ET_0) and the crop coefficient (K_c) are considered. The K_c value represents the evapotranspiration of a crop under optimal conditions to produce maximum yields. The main factors that affect the K_c value are the type of crop, sowing dates, rate of crop development, duration of the growing season, and climatic conditions (USDA-NRCS, 1993). The Kc is the relationship between the actual evapotranspiration of each crop and the ET_0. The K_c value is a dimensionless number (normally between 0.1 and 1.2) (Allen et al., 2006). Kc coefficients for this study were taken from Allen et al., (2006) (see Table A14). For annual crops (rice, corn, and soybeans) and perennial crops, the Kc value of the medium crop development stages was assumed as a constant value for each month of the year.

Equation A-14

$$ET_c = K_c * ET_0$$

Where, ET_c = crop evapotranspiration (mm day^{-1}); K_c = crop coefficient; ET_0 = reference crop evapotranspiration (mm day^{-1}).

Table A14. Kc coefficient based on Allen et al. (2006).

Crop	Kc coefficients		
	$Kc_{Initial}$	Kc_{Medium} [b]	Kc_{Final}
Rice	1.05	1.2	0.9
Corn	n/a	1.2	0.6
Plantain	0.5	1.1	1.0
Soybean	n/a	1.15	0.5
Cassava	0.3	0.8	0.3
Oil palm [a]	0.6	0.9	n/a
Sugarcane	0.4	1.25	0.75
Acacia	0.95	1.0	1.0
Pastures - extensive grazing	0.3	0.75	0.75
Pastures - rotation	0.4	0.85	0.85

[a] Data taken from Cenipalma, unpublished studies.

[b] Kc value of the medium crop development stages was assumed as a constant value for each month of the year for all crops.

The **available water-holding capacity** (AWC) of the soil is the amount of water that a soil can store and that is available for use by plants (USDA-NRCS, 1993). The water-holding capacity of the soil depends on the texture and structure of the soil and the depth of the plant roots. Only a portion of the available water is easily used by the plant. To identify the soil water storage capacity available to the plant, the value of sheet quickly exploitable water was calculated following *Equation A-15*. The data for this calculation were taken according to the predominant type of soil texture in each subregion. Table A15 shows the input data considering the most predominant agricultural soil texture by subregion. Soil can be considered as a reservoir of water, but not all water resource is available to the plant, but only that which is retained by the soil in the range between field capacity (FC) and permanent wilting point (PWP) (Alvarez et al., 2006). FC and PWP are considered as soil moisture constants. The values of these constants vary for the different types of soils and for the different horizons of the soil profile (Alvarez et al., 2006).

Equation A-15

$$AWC = \frac{(FC - \mathrm{P}WP)}{100} * BD * \mathrm{ERD}$$

$$RAW = \mathrm{AWC} * \mathrm{MAD}$$

Where, AWC = available water-holding capacity of the soil (mm); FC Field capacity (%); PWP = Permanent wilting point (%); BD = Bulk density (g/cm^3); ERD = Effective root depth (cm); RAW = Readily available water is the water that a plant can easily extract from the soil (mm); MAD = Maximum allowable depletion that is a fraction from 0 to 1 (dimensionless).

Table A15. Input data to calculate the available water-holding capacity and Readily available water for each crop considering the main texture of the soil by subregion, based on data from Allen et al. (2006)

Cover type	ERD	MAD	Highplain [a]				Foothill/Flooded plain [b]			
			FC	PWP	BD	RAW	FC	PWP	BD	RAW
Rice	75	0.2	31	11	1.4	42.0	18	8	1.4	21.0
Corn	100	0.5	31	11	1.4	140.0	18	8	1.4	70.0
Soybean	95	0.5	31	11	1.4	133.0	18	8	1.4	66.5
Plantain	70	0.35	31	11	1.4	68.6	18	8	1.4	34.3
Cassava	65	0.35	31	11	1.4	63.7	18	8	1.4	31.9
Oil palm	60	0.5	31	11	1.4	84.0	18	8	1.4	42.0
Pasture	100	0.6	31	11	1.4	168.0	18	8	1.4	84.0
Sugarcane	60	0.5	31	11	1.4	84.0	18	8	1.4	42.0
Acacia	205	0.5	31	11	1.4	287.0	18	8	1.4	143.5

[a] Soil texture for the highplain subregion corresponds to silt loam.
[b] Soil texture for the foothill and flooded plain subregions corresponds to sandy loam.
ERD = Effective root depth (cm)
MAD = Maximum allowable depletion (dimensionless)
FC = Field capacity (%)
PWP = Permanent wilting point (%)
BD = Bulk density (g/cm^3)
RAW = Readily available water (mm)

4.2A Crop water irrigation calculations

Irrigation water is generally used in times when drought is expected in crop areas to meet the crop water needs (ET_c) and to achieve crop yields (USDA-NRCS, 1993). A water deficit can generate moisture stress affecting the expected yield of the crop, thus, it is essential to maintain soil moisture, especially in periods of plant growth (IDEAM, 2019). Based on the result of crop water need (ET_c), effective precipitation, and projected land-use area per scenario, the total irrigation water requirement (IWR) is calculated only for perennial crops (i.e., cassava, plantain, oil palm, sugarcane, acacia) because the annual crops (i.e., rice, corn, soybean, pasture) in the region are rainfed (IDEAM, 2019). See *Equation A-16* and *Equation A-17*.

Equation A-16

$$\boldsymbol{IWR_x = \frac{CWR * A_x}{IE_i}}$$

Equation A-17

$$\boldsymbol{CWR = ET_c - EP}$$

Where, IWR_x = Irrigation water requirements for land cover type x (m^3); CWR = Crop water requirements (mm); A_x = cultivation area for land cover type x (m^2); $ET_{c,i}$ = crop evapotranspiration for land cover type x (mm); IE_i = irrigation efficiency by type of system i (%) (see Table A16); i = irrigation system; EP =effective precipitation.

There are many types of irrigation systems, in which the water is distributed to the entire field involving greater or lesser efficiency in the use of water (USDA-NRCS, 1993). According to the efficiency of the irrigation systems, we assume an irrigation efficiency for each scenario as shown in Table A16. For the reference scenario and low scenario, surface irrigation by flooding is assumed, which has the lowest efficiency in the use of water. For the medium scenario, although surface irrigation system is used, it is assumed that the furrows have adequate soil preparation, leveling, and hilling-up of the plants, making the water efficiency use better than that of flood irrigation. The high intensification scenario assumes the use of a more efficient system, i.e., sprinkler irrigation that consists of the distribution of water through specific points by means of sprinklers that simulate the fall of rainwater.

Table A16. Irrigation systems related to each scenario and the irrigation efficiency per system.

Scenario	Irrigation System	Irrigation efficiency [a]
Reference	Surface irrigation by flooding	30%
Low	Surface irrigation by flooding	30%
Medium	Surface irrigation by furrows	50%
High	Sprinkle irrigation	80%

[a] Index used to quantify the use of irrigation water to a crop area based on (USDA-NRCS, 1993) and (FAO, n.d.).

4.3A Cattle water balance calculations

To estimate the amount of water intake by cattle, equation (7) is considered. Table A17 shows the input data for the calculation. The maximum temperature and relative humidity are taken at a regional level from IDEAM (2020) and correspond to average data for the period 1999-2019 (i.e., T_{max} = 27.9 °C, HU 80.4%).

Table A17. Input data for calculating the cattle water intake based on information from Ramirez-Contreras et al. (2021).

Scenario	DMI (kg/day/animal)	BW (kg)	MBW (kg)	UA/ha	# animals		
					Highplain	Foothill	Flooded
Reference	12.03	380	86.1	0.6	4,272,970	2,636,236	2,421,954
Low	14.51	380	86.1	1.0	3,195,356	4,069,732	1,799,695
Medium	15.09	400	89.4	1.5	2,216,092	4,864,238	1,237,003
High	16.03	450	97.7	2.0	1,894,576	4,158,523	1,057,536

DMI= Dry matter intake data from
BW = live weight or body weight
MBW = is the metabolic body weight in $kg^{0.75}$
Number of animals are calculated based on the Unit Animal (UA) per hectare.

5A. Parameters for calculation of the economic performance

The NPV is calculating based on the model developed by Fontanilla-Díaz et al. (2021). The linear programming model contains regional information taken through field surveys. The model calculations comprise an annual general analysis of agricultural production at the farm-level. Because the model analyzes crops by annual rotation, we adjust condition the model to the requirements set out in the intensification scenarios and the reference scenario of our study. We also adjusted the model to calculate the NPV of all the crops considered in our study. To calculate the NPV, a cash flow of several annual periods is considered. In each year, the revenue is brought, and the corresponding costs (capital and operating costs) are subtracted. Year zero is considered as the investment period (present) and all values reported in subsequent periods are considered future values. The NPV is calculated by adding all the net revenue for each period (brought to present value). To bring future values to present value, an opportunity rate is discounted from them. To complement the economic viability, the internal rate of return (IRR) is calculated. IRR can be understood as the rate at which the money invested in a business is rented (Sapag and Sapag, 2008). The IRR makes the sum of the net cash flows of each year during the useful life of the project equal to the initial investment of period zero. The IRR must be greater than or equal to the discount rate (Sapag and Sapag, 2008).

Since prices from commodities fluctuate according to the dynamics between supply and demand at a global level, commodities experience high and low prices along time (Contexto Ganadero, 2017). We considered historical real prices data sets for each agricultural product under assessment and estimated the range in which prices have fluctuated so we could encompass future price uncertainty. We used five years of price data reported by FAOSTAT for cattle, food crops, and energy crops (beef, rice, corn, soybeans, cassava, plantain, acacia wood, oil palm fruit, and sugar cane) (FAO, 2021). On the other hand, it must be highlighted that in Colombia, there are no price control for agricultural goods. The sale price accounts for commodity price dynamics at a global level and short-term shocks, such as changes in the supply volume caused by climatic variations and sanitary status. All data for calculating these financial indicators are in section 5A.

Table A18. Yield levels and cattle densities for the reference and agricultural intensification scenarios based on our previous study (Ramirez-Contreras et al., 2021)

Characteristics		**Scenarios 2030**			
		Reference	Low	Medium	High
Yield food crops (t ha^{-1} yr^{-1})	Rice	5.0	5.1	5.3	6.0
	Corn	5.5	6.0	6.0	7.0
	Oil palm (FFB)	14.5	16.0	20.0	23.0
	Plantain	6.5	7.5	8.0	8.5
	Soybean	2.5	2.5	2.8	3.0
	Cassava	14.0	15.0	18.0	20.7
Cattle productivity (AU ha^{-1}) [a]	Cattle	0.6	1.0	1.5	2.0
Yield energy crops [b] (t ha^{-1} yr^{-1})	Sugarcane	n.a	n.a	84.3	85.4
	Acacia	n.a	n.a	71.0	78.8
	Oil palm (FFB)	n.a	n.a	20.0	23.0

[a] AU = animal unit. One AU is equivalent to 450 kg of average animal-live-weight (Fedegan, 2018).
[b] For the medium and high scenarios, it is assumed that all surplus land generated from the intensification is used either for sugarcane, palm oil, or acacia.

Table A19. Average input data for the economic regional evaluation of food crops per scenario

Crop/scenarios		Land rent	Crop establishment	Fertilization and agrochemicals	Harvest	Others
Rice[a]	R	54.2	225.2	580.3	134.9	13.5
	L	54.2	225.2	587.6	136.2	13.5
	M	54.2	225.2	602.3	138.8	13.5
	H	54.2	225.2	656.1	148.4	13.5
Corn[a]	R	54.2	257.6	539.3	179.4	60.4
	L	54.2	281.0	572.7	189.5	62.3
	M	54.2	281.0	572.7	189.5	62.3
	H	54.2	327.8	639.5	209.8	66.2
Soybean[a]	R	54.2	116.3	461.4	81.2	27.1
	L	54.2	116.3	464.1	81.4	27.1
	M	54.2	116.3	488.4	82.9	27.1
	H	54.2	116.3	506.4	83.9	27.1
Cassava[b]	R	94.8	267.8	143.3	197.9	.
	L	94.8	286.9	151.2	212.0	.
	M	94.8	344.3	174.8	254.4	.
	H	94.8	396.7	196.3	293.2	.

Plantain[c]	R	94.8	433.2	132.0	147.4	54.2
	L	94.8	433.2	123.7	138.2	54.2
	M	94.8	433.2	123.7	138.2	54.2
	H	94.8	433.2	131.5	146.8	54.2
Oil Palm[d]	R	169.4	41.7	331.5	174.3	218.2
	L	169.4	41.7	355.9	191.7	220.0
	M	169.4	123.2	376.4	237.4	224.5
	H	169.4	155.6	424.5	271.8	228.0

For scenarios: R = reference; L = low; M = medium; and H = high

[a] Data based on information from (Fontanilla, 2019).

[b] Cassava costs data (ADS, 2019)

[c] Plantain costs data (MADR, 2018b)

[d] Oil palm costs based on (Mosquera et al., 2018b) (Mosquera et al., 2018a) (Mosquera-Montoya et al., 2020)

Table A20. Average input data for the economic regional evaluation of energy crops per scenario

	Sugarcane [a]		**Acacia** [b]		**Oil palm** [c]	
	M	H	M	H	M	H
Cash outflow (USD ha^{-1})						
Seeds	67.9	67.9	6.4	6.4		
Irrigation	300.3	300.3			123.2	155.6
Fertilizers/agrochemicals	274.3	274.3	15.1	16.8	332.4	380.5
Machinery rent	245.7	245.7				
Labor	108.9	108.9	63.7	63.7		
Technical assistance					23.7	27.2
Pruning					20.2	20.2
Weed control					43.9	43.9
Sanitary control					87.5	87.5
Planning and monitoring					112.1	112.1
Land rent	182.8	182.8	53.3	53.3	169.4	169.4
Harvest and transport			46.5	51.6	237.4	271.8
Others	78.1	78.1	4.6	4.6	93.1	93.1
Cash inflow (USD ha^{-1})						
Income	1,365.2	1,381.6	403.3	447.3	1,662.0	1,902.6
Net income	107.2	123.6	149.9	181.8	419.1	541.4
NPV (5%)	1,579.2	1,977.7	1,237.3	1,470.0	3,946.4	5306.4
IRR (%)	16.9	18.7	15.6	17.6	14.6	16.0

All prices are taken to USD in 2020 base on the information by Banco de la Republica, (2021).

[a] Sugarcane costs based on (MADR, 2015) (DANE, 2015).

[b] Acacia costs based on (CONIF, 2013) (Cuong et al., 2020) (Trujillo, 2014).

[c] Oil palm costs based on (Mosquera et al., 2018b) (Mosquera et al., 2018a) (Mosquera-Montoya et al., 2020).

Table A21. Average input data for the economic regional evaluation of cattle production per scenario. Data based on information from (Fontanilla, 2019).

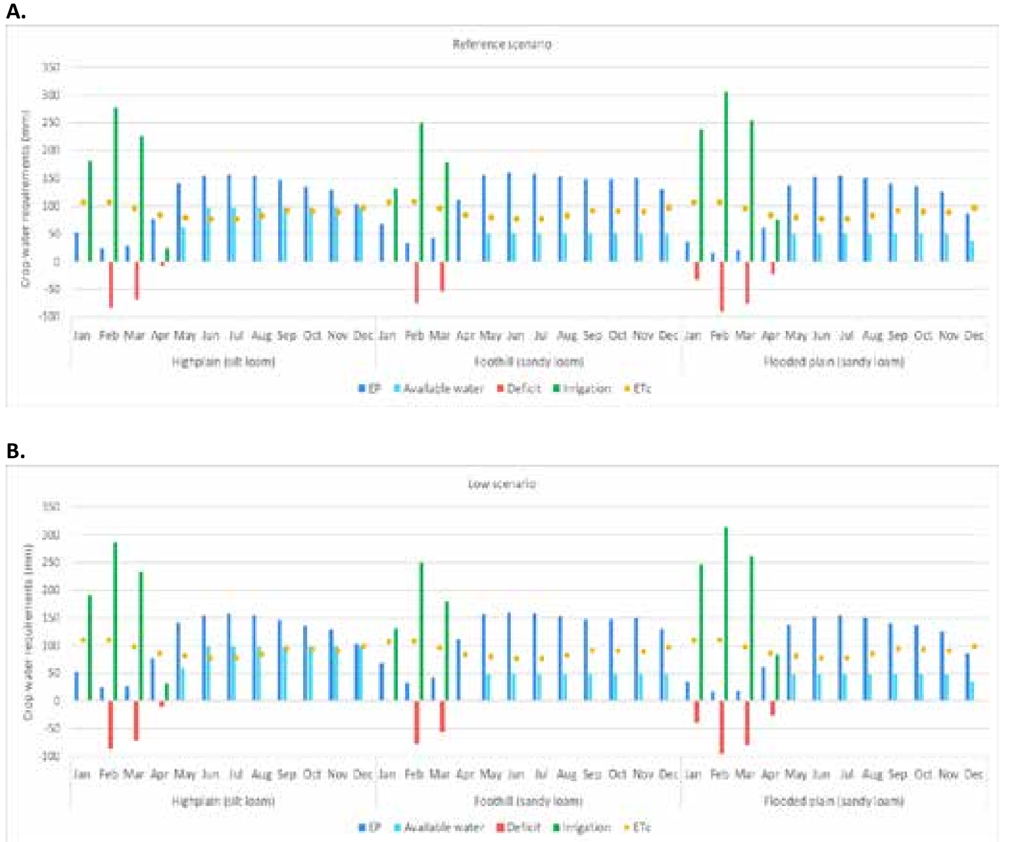
	Reference	Low	Medium	High
Cash outflow (USD ha^{-1})				
Purchase cost of animals	34.6	90.7	217.2	319.1
Pasture implementation			97.5	97.5
Sorghum forages implement [a]			100.7	142.2
Fences	3.5	3.5	6.0	12.5
Labor	13.7	15.3	18.8	30.4
Animal water supply			1.0	1.0
Water irrigation for feed			5.7	5.9
Lime input and applicator (feed)			31.2	32.5

Supplementary salts	7.9	13.7	19.7	27.1
Vaccines	0.5	0.8	1.2	1.3
Technical assistance	0.1	0.1	0.1	0.1
Rent land	54.2	54.2	54.2	54.2
Cash inflow (USD ha^{-1})				
Income	132.4	221.0	644.3	970.9
Net income	19.6	44.0	99.8	264.3
NPV (5%)	101.9	297.7	642.9	2,756.5
IRR (%)	8.0	9.9	9.2	20.1
[a] Sorghum forage costs from (Bernal et al., 2014).				

6A. Results of monthly soil-water balance by subregion

Figure A-3 shows the graphs for monthly crops evapotranspiration, effective precipitation, available water capacity that the soil can store, water deficit, and the total irrigation water for perennial crops over the dry season considering the main soil texture by subregion.

Looking at agricultural crops, the greatest water deficit is registered in the cultivation of rice, corn, soybean, and plantain for all three regions (Figure A-3). The lowest water deficit is reported by the cassava cultivation. Pastures for cattle production also report a low water deficit similar to the reported value for cassava. For energy crops, the highest water deficit is found for sugarcane, while the lowest deficit corresponds to acacia and oil palm cultivation.



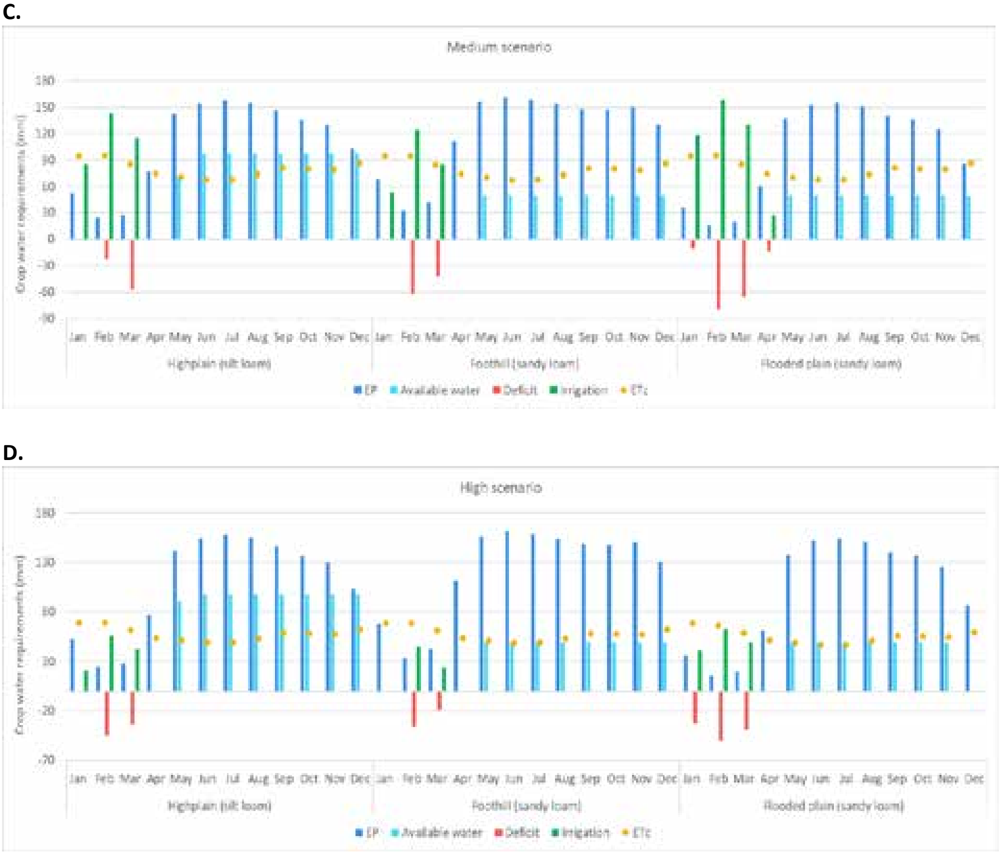


Figure A-3. Monthly soil-water balance for all crops by scenario by subregion. EP = effective precipitation; ET_c = crop evapotranspiration; Available water capacity = the amount of water that a soil can store that is available for use by plants; Deficit = when water demand exceeds supply.

7A. Results of cattle water intake by subregion

Table A22. Cattle water intake (WI) over year, million m^3 $year^{-1}$ by scenario by subregion.

Scenario	Subregion		
	Highplain	Foothill	Flooded plain
2018	9.1	19.9	5.1
Reference	28.7	17.7	16.3
Low	22.9	29.1	12.9
Medium	16.6	36.5	9.3
High	15.6	34.3	8.7

8A. Results of economic performance

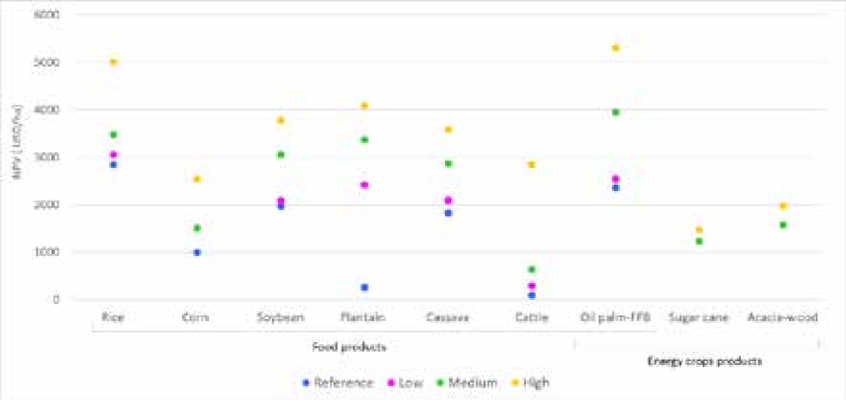


Figure A-4. Net present value of food crops, energy crops, and cattle production by scenario. Energy crops are only cultivated in the medium and high scenarios. Note that for corn the low and medium scenario dots overlap.

Considering the fluctuations of the last five years reported worldwide by FAOSTAT for the market prices of both food products and bioenergy raw materials, Figure A5 shows the variation range in the NPV for all products in the high scenario. The ranges of variation in market prices for rice, corn, soybeans, cassava, acacia wood, and beef, shown in Table A23, do not greatly affect the NPV of these products. While the ranges of variation in market prices for plantain, oil palm fruit (FFB), and sugarcane generate large differences in NPV. The NPV of oil palm fruit and sugarcane is extremely sensitive to changes in market prices and production yields. Although in the high scenario the production yields are high, a negative fluctuation of about 21% in market prices generates a negative NPV for sugarcane, making this raw material unprofitable.

Table A23. Ranges of variation in market prices based on FAOSTAT (FAO, 2021). Data in percentages (%)

	Rice	Corn	Soybean	Cassava	Plantain	FFB	Sugarcane	Acacia	Beef
Tendency (+)	4	9	12	11	20	17	26	10	5
Tendency (-)	-3	-7	-6	-8	-26	-22	-21	-10	-3

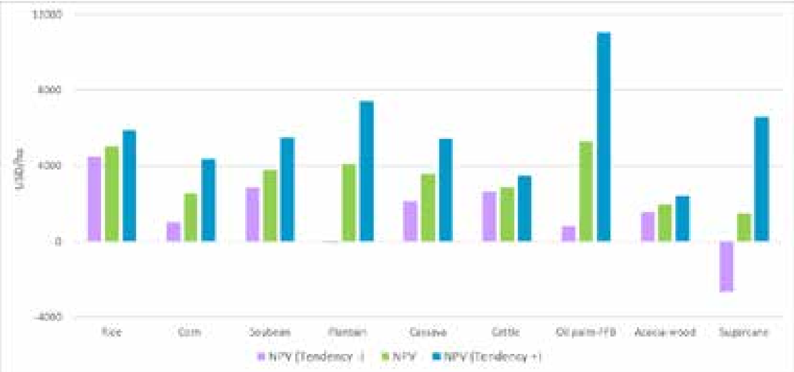


Figure A5. Net present value considering the variation of the market prices for all the products in the high scenario.

Chapter 6

Conclusions & recommendations

6.1 Research context

To reduce global GHG emissions to maintain average temperatures below 2 °C in relation to pre-industrial levels (UN, 2015), the production and utilization of biomass for bioenergy can play an important role (IEA, 2021). The use of biomass for energy purposes can contribute to reducing the dependence on fossil fuels because of its versatile applicability in transport and in generation of electricity and heat (IEA, 2021), and its contribution to the energy matrix diversification to achieve benefits in terms of energy security and resilience (IEA, 2021) (IRENA, 2021). The use of bioenergy is mainly driven by the need to reduce GHG emissions. In addition, it can exert both positive and negative sustainability impacts (e.g., GHG emissions, biodiversity, water, soil quality, land tenure, food security) (IEA Bioenergy, 2015) (Creutzig et al., 2015) (Diaz-Chavez et al., 2016). The impacts and sustainability concerns associated with bioenergy often relate to land use and (indirect) land-use change (I)LUC) caused by the production of biomass feedstock (IPCC, 2020). Therefore, it is important to understand the preconditions, management strategies, and governance options that can ensure that land-use change with respect to bioenergy utilization is minimized to enable mitigation of climate change in a sustainable manner. The use of certification schemes can help to avoid negative environmental and socio-economic impacts of biomass production and facilitate the sustainable production of bioenergy (van Dam et al., 2010) (Diaz-Chavez et al., 2016). Certification schemes can be voluntary (e.g., ISO 13065, ISCC, and RSPO) or mandatory (e.g., Renewable Energy Directive or RED).

Presently, in Latin America, the production and use of bioenergy are promoted as a strategy to address climate change (Rodríguez et al., 2017) (UNFCCC, 2020). This world region demonstrates considerable experience with bioenergy production(Rodríguez et al., 2017) and several countries in Latin America are significant bioenergy producers. Latin America demonstrates the potential of expansion of its agricultural area, which can be used to increase biomass production (Rodríguez et al., 2017). Furthermore, Latin America has the option to improve cropland and livestock yields to generate surplus land that could be used for biomass production with a low risk of ILUC (Souza et al., 2015). Several studies have projected the bioenergy potential for Latin America. For example, the potential production of bioenergy in Latin America in 2050 is estimated to be 47-110 EJ/yr for sustainable energy crop production in unused grasslands (Searle and Malins, 2015). Daioglou et al. (2019) projected a potential production of bioenergy in Latin America in 2050 ranging from 20 to 25 EJ/yr depending largely on population growth, economic growth, food demand, and technological development (i.e., yields). The potential applicability of new non-food crop options and the use of agricultural residues for the production of bioenergy also depends on the climatic conditions of each area, land availability, good management practices, and the support extended by national and international legislation and policy programs (Plath et al., 2016) (Garcia-Nunez et al., 2016) (Younis et al., 2021).

Colombia is recognized as a key country for the production and utilization of bioenergy in Latin America (Brito-Cruz et al., 2016). In recent decades, Colombia has demonstrated experience in the production and use of biofuels and, more recently, in bioelectricity production and use (MADR, 2016). However, the contribution of bioenergy to the national energy sector has been relatively low, making up less than 50 PJ/year (12%) of the more than 400 PJ/year in the road transport sector and close to 200 PJ/year (2%) in the electricity sector (Asocaña, 2016) (UPME, 2016). Colombia designed the "Strategy 2050 ", which plans for Colombia to emerge as a climate-resilient country with a carbon-neutral economy by the year 2050 (Gobierno de Colombia, 2021). Moreover, the Colombian government defined the national policy strategy for the development of the country's bioeconomy. This strategy assumes that a sustainable bioeconomy requires sustainability of the country's biological resources, in addition to the sustainability of production, consumption, and the reuse of materials (circular economy) (Gobierno de Colombia, 2020). The Orinoquia region is deemed a crucial area for the development of bioenergy in Colombia (CIAT & CORMACARENA, 2017).

There is an increasing need to formulate different land use strategies that allow simultaneously meeting the expected rising demand for food, feed, fiber; sustainably producing biomass for energy and material applications; and conserving nature (IEA Bioenergy, 2014) (Junginger et al., 2019) (Prüssmann et al., 2020). In view of these different demands, it is important to consider the following for sustainable production of bioenergy in Colombia: 1) increase the national energy basket ; 2) net environmental contribution in terms of reducing GHG emissions to comply with the country's environmental commitments of emissions and to reduce the net impact on water and biodiversity resources; 3) contribution to job creation, particularly in rural areas; and 4) adoption of scientific and technological developments that contribute to reducing impacts and producing bioenergy efficiently (UPME, 2016b). Therefore, it is necessary to propose measures and strategies to increase the efficiency of land use and to reduce its associated impacts, as proposed in several previously published studies (Castanheira et al., 2014) (Batidzirai et al., 2016) (Gerssen-Gondelach et al., 2017) (de Souza et al., 2019) (Younis et al., 2021).

Among the strategies implemented for more sustainable biomass production, the role of certification schemes for addressing sustainability concerns and the role of integrated assessments for strengthening governance have been identified (Diaz-Chavez et al., 2016) to be of particular importance in the case of Colombia. Although Colombian policies push for GHG emission reduction and sustainable development at large, a route to implement specific criteria and indicators for sustainability in the use of biomass from crops has not been defined. Thus, an analysis of the key criteria and indicators that imply the production of biomass and its value chain, together with its application, will contribute to the address of the requirements for sustainable biomass production. Furthermore, agricultural intensification is important to meet the diverse needs of the land and to reduce the impacts of direct LUC and the risk of ILUC (Gerssen-Gondelach et al., 2017).

The complexity of issues such as biodiversity, water, and land use warrant integrated assessments that will help strengthen and validate the protection of natural resources and the sustainable production of bio-based products. In addition, these integrated approaches need to be able to quantify the potential for improvement in different farming systems and associated environmental and socio-economic impacts. In the literature, there are already attempts at such an integrated analysis concerning impacts of bioenergy (Howells et al., 2013) (Thrän et al., 2016) (Vera et al., 2020) (Wu et al., 2018), but most of them have focused only on prevention of (I)LUC and its related GHG emissions (Brinkman et al., 2018) (Castanheira et al., 2015) (de Souza et al., 2019) (Gerssen-Gondelach et al., 2017) (Kadiyala et al., 2016). Some studies have also focused on the analysis of bioenergy and its socio-economic impacts (Walter et al., 2011) (Wang et al., 2014) and a few studies addressed the impacts of bioenergy production on biodiversity and water (Mekonnen et al., 2018) (Rincón et al., 2014). Analyses that address multiple environmental impacts and the economic performance at the same time are, however, scarce for Colombia. Moreover, such an integral impact analysis is important to understand the multiple impacts that agricultural intensification and increased bioenergy crop production can have, including potential trade-offs across impact categories, and to identify optimal land use and management strategies (Creutzig et al., 2015).

6.2 Objective and research questions

This PhD thesis aims to i) evaluate the environmental and economic performance of biomass production for energy and materials in Colombia and ii) to define strategies to work towards a more sustainable production of biomass.

The aims are addressed by the following research questions:

7. What are the environmental and economic impacts of different biomass production systems at national and regional level considering different management practices and land use scenarios?
8. What are the key measures to improve the environmental and economic impacts of biomass production in the future?
9. How can analytical frameworks be designed to facilitate the regional integrated assessment of land use and impacts of bioenergy scenarios and how can such frameworks strengthen governance for future sustainable biomass production?

Table 9 gives an overview of the chapters of this thesis in which these research questions were addressed.

Table 9. Structure of the thesis

Chapter	Topic	Spatial and temporal focus	Energy crops	RQ1	RQ2	RQ3
2	A review of key international biomass and bioenergy sustainability frameworks and certification systems and their application and implications in Colombia.	Global; Colombia/ current status	Any energy crop	++	+	+
3	The GHG emissions and economic performance of the Colombian palm oil sector; current status and long-term perspectives.	Colombia/ current and future status	Oil palm	++	+++	+
4	GHG balance of agricultural intensification & bioenergy production in the Orinoquia region, Colombia.	Orinoquia/ current and future status	Sugarcane, oil palm, and acacia	++	+++	+++
5	Environmental impacts and economic performance of agricultural intensification and bioenergy production in the Orinoquia region	Orinoquia/ current and future status	Sugarcane, oil palm, and acacia	++	+++	+++

The symbols (+) indicate the level the research question is addressed by a chapter.

6.3 Summary of the main results

Chapter 2

Several organizations and governments have developed certification schemes for agricultural and biomass production that can be used to reduce negative impacts on the environment, society, and economy. The three primary aims of this chapter were: 1) to conduct a state-of-the-art review of key sustainability frameworks for bioenergy at the international level (criteria, status, and improvements); 2) to determine the manner in which a few initiatives have been implemented in Colombia); and 3) to identify the drivers of environmental, social, and economic issues that could affect the establishment of a bio-based economy in Colombia. The guideline for this study was the Renewable Energy Directive (RED 2009/28/EC), which is mandatory for the use of renewable energy in Europe. This directive was updated in 2015 (Directive (EU) 2015/1513) to add new guidelines for reducing ILUC, for limiting the use of agricultural land for energy purposes, and for increasing the amount of GHG emission savings. Based on this, a few voluntary certification systems have also updated their indicators to adjust to the RED.

In total, eleven certification systems for sustainable bio-based products or sustainable biomass were evaluated, of which ten systems were related to international certification systems and one was a certification system specific to Colombia (Icontec-GTC 213). These certification systems comprise more than 50 sustainability criteria/indicators that cover social, environmental, and economic aspects. It was noted that there remains a greater focus on environmental issues than on a balance among essential sustainability issues. However, social, and economic issues have recently gained prominence within the requirements of the standards. Most certification systems analyzed have updated their criteria based on the criteria developed by the European Commission through the Renewable Energy Directive (RED) (EU2015/1513).

The following four key themes are highlighted among all standards: ILUC, GHG, water, and biodiversity.

- The inclusion of ILUC is considered the most important update of the standards such as RED, Better Biomass, and RSB due to this is one of the key impacts attributed to bioenergy production. For RED, ILUC was included to reduce the GHG emissions generated by biofuels and to prevent excessive use of land destined for food production to produce biofuels. For the RSB and Better Biomass standards, the emphasis is on increasing crop yield to reduce ILUC.
- As a RED requirement, there is an obligation to include GHG emissions within sustainability requirements and publication of the emission records. Moreover, the use of GHG calculation tools was highlighted to facilitate homogenization and comparison of the information obtained. To this end, the BioGrace calculator has been recognized by the European Commission as a voluntary scheme for bioliquids and biofuels.
- All the standards recognize the need for water conservation from three points of view: availability, efficiency of use, and quality; but the ways by which these topics were addressed differed. The ISCC and RTRS prioritize the care of natural wetlands to maintain water availability. Better biomass generation, ISCC, RTRS, GTC 213, and Bonsucro emphasize the efficiency of water use for irrigation. GBEP, ISCC, RSPO, RED, RTRS, and SBP consider the impact of agricultural practices on water quality and mandate the measurement of parameters such as N, P, and pesticides. ISO 13065 is a comparatively strict guideline because it mandates the identification of physicochemical and biological parameters associated with possible impacts, such as eutrophication and oxygen depletion.
- All standards emphasize the maintenance or improvement of HCV areas. Additionally, standards require the presence of ecological corridors to maintain a buffer zone around the project area and to facilitate the movement (flow) of wild species. ISCC has a strict requirement to protect land with HCV or high carbon content.

Although the standards have included a greater number of social indicators within their requirements, it is necessary to include details on specific methodologies that facilitate an accurate quantification of social welfare at the local, regional, and national levels. It is also necessary to focus on the indirect impacts beyond the regional (sectoral) borders. The main social issues emphasized in the analyzed certification systems were rural and social development, food security, and human, labor, and land rights. The standards in which social issues were presented with the highest priority were ISCC, RSB, and RSPO. Although the GBEP standard markedly focuses on food security, it does not include specific indicators for issues such as child labor, the welfare of employees and their families, free association, and participation of women and indigenous communities in projects.

In Colombia, the production of sustainable bio-based products is an optimistic scenario. It has been determined that the country possesses a substantial amount of land that is suitable for cultivation without triggering the generation of deforestation problems. However, this also presents several challenges with respect to the production or seeding of biomass. For this reason, the national government has engaged efforts to provide laws to protect the environment (climate, soil, biodiversity, and water), to increase the role of renewable energy, to reduce GHG emissions, to stimulate rural development, and to establish competitive sectors with a vision of climate finance. In other words, the plan is to incorporate climate change into the economic and financial planning of the country. Additionally, the development of a bioeconomy represents an opportunity to address the challenges of food security, climate change, and the generation of clean energy. However, certain complex issues surrounding biodiversity, water, and soil remain, which require the integrated use of rigorous national laws for the protection of natural resources and the use of certification systems for sustainable products.

Chapter 3

Energy crop expansion can increase land demand and can generate displacement of food crops, which impacts GHG emissions mainly through land use change. Increased agricultural productivity can compensate for this issue. This chapter discusses the analysis of GHG emissions and economic performance of the Colombian palm oil sector. Additionally, the net energy ratio (NER) of the biodiesel production lifecycle was also analyzed. Collection of the total primary data from the oil palm sector in Colombia entails a tremendous challenge. However, in this study, we could collect data regarding the production of 70% of the fresh fruit bunches (FFB). The analysis is based on the consideration of the prevailing situation of the crude palm oil (CPO) chain and two future scenarios wherein the CPO production chain is intended to be optimized to reduce GHG emissions. Future scenario A will enable the production of biodiesel (BD), biogas, cogeneration, and compost, while future scenario B will enable the production of BD, biogas, cogeneration, and pellets. The Colombian oil palm sector was selected for evaluation because oil palm has been deemed an energy crop that could significantly contribute toward avoiding (I)LUC and its related GHG emissions. Additionally, with this crop, an average annual growth rate of 7% over the last 10 years has been observed and the agricultural activity involving the crop is projected to increase nationwide (Fedepalma, 2020). By the year 2020, the production value for the oil palm sector (i.e., CPO and palm kernel) represented 9.1% of the national agricultural GDP (Fedepalma, 2020).

The findings of this study suggest that there is significant potential for improving the current palm oil production chain. In the present situation, the average carbon footprint along the CPO production chain is −689.8 kg CO_2eq t^{-1} CPO, wherein LUC, CH_4 emissions from palm oil mill effluent (POME), and chemical fertilization are considered the primary factors contributing to GHG emissions. Although few mills have already reported the elimination of CH_4 emissions from POME through biogas capture and subsequent flaring, there remains considerable opportunity for the reduction of CH_4 emissions from the remaining mills in the country.

In future scenarios, improvements in the CPO production chain will facilitate a 55% decrease in GHG emissions compared to the present situation. The impact of land use change must be mitigated to reduce GHG emissions. Therefore, a sustainable oil palm expansion should be observed in areas with low carbon stocks or areas suitable for this crop (e.g., cropland, pastureland), with the avoidance of deforestation of natural forests. Moreover, GHG emissions can be reduced through the strategies of good agricultural practices, such as a) reduction in the use of chemical fertilizers with high carbon footprints (e.g., ammonium nitrate), b) application of soil conditioners such as compost, c) increase in crop yield and CPO yield per ha, d) reduction of diesel consumption, and e) facilitation of biogas capture. Additionally, whenever possible, discharges from the POME system can be used for water irrigation in nearby plantations, and biomass can be used to produce bio-based products.

Furthermore, NER analysis of biodiesel production showed a renewable energy gain compared to the fossil energy input in the production system.

For all scenarios assessed, crop operational costs represent the greatest investment. However, it is expected that in the long-term scenarios, the total capital expenditure (CAPEX) and operational expenditure (OPEX) will decrease by approximately 20% in comparison with the current situation. The sale of surplus energy and pellets can contribute toward approximately 5%–10% of the total income. The approach discussed in this chapter provides an oil palm sector value chain perspective to understand the significant potential for improvement in the GHG balance. The method clearly highlights the importance of using industry-specific data and the importance of evaluating the entire value chain. By including considerations such as yield improvement, selection of low-carbon stock lands, scaling up of biogas, pellet, and compost production, and cogeneration, important long-term cost-effective options can be explored.

Chapter 4

Increasing agricultural productivity may offset the expansion of energy crops on surplus land, thereby decreasing the demand for land. In this chapter, the net GHG balance of the Orinoquia region for the year 2030 has been calculated considering i) agricultural intensification of food crops and beef production, and ii) bioenergy generated from energy crops produced on the obtained surplus land. The GHG balance was evaluated for three agricultural intensification scenarios (low, medium, and high) and a reference scenario, in combination with the following three bioenergy production routes: ethanol from sugarcane, biodiesel from oil palm, and electricity production from acacia.

The results showed that the land area required in the Orinoquia region to meet the demand for food crops and beef in the reference scenario (13.8 Mha) was approximately two times higher than the demand for land in the year 2018 (6.8 Mha). The most considerable demand for land use is for beef production in extensive grazing systems, accounting for more than 90% of the agricultural area. Although the total land demand is within the available agricultural land of the region (15.5 Mha), it is dependent on the conversion of natural vegetation to pastureland, which will result in substantial amounts of LUC-related emissions.

Less land area was required in the three intensification scenarios due to an increase in agricultural productivity. Particularly, the medium and high intensification scenarios relied on the utilization of markedly less area to produce the same amount of food compared to that produced in the year 2018. In the medium and high scenarios, the increase in cattle productivity was key to the approval of 10% and 38% of the current cattle production area for bioenergy feedstock production, respectively. Therefore, a land surplus of 0.6 and 2.4 Mha may be generated for the medium and high scenarios, respectively. Bioenergy potential production on the surplus land obtained is projected at 36 to 368 PJ per year and is considered as low-ILUC-risk because the use of surplus land minimizes concerns related to competition for land and displacement effects.

The medium and high agricultural intensification scenarios resulted in decreased LUC-related emissions compared to the reference scenario, since no natural vegetation (shrubland) could be converted, and degraded pastures were improved for use as managed pastureland. The application of better agricultural practices when intensifying agricultural production can aid reduction of up to 83% of the positive GHG emissions of the reference scenario. As the cattle areas responsible for the generation of surplus land are expected to consist largely of degraded pastures, the conversion of degraded pastures to energy crops can result in substantial carbon sequestration. Furthermore, the options assessed for bioenergy production (biodiesel, bioethanol, or bioelectricity) result in more than 100% reduction in GHG emissions compared to their fossil fuel equivalent (diesel, gasoline, and coal, respectively), which meets GHG saving requirements prescribed in the RED II. Consequently, consideration of an integrated perspective of agricultural land use enables sustainable production of both food and bioenergy.

Chapter 5

Agricultural intensification and increased bioenergy production on the resulting surplus land highlights concerns not only regarding GHG emissions but also those pertaining to other environmental impacts such as water depletion and biodiversity loss. Additionally, the economic performance of such strategies is poorly understood. This chapter describes the conduction of an integrated analysis of the impacts of LUC on biodiversity, water, and economic performance due to agricultural intensification and bioenergy production by applying LUC projection data obtained in the study conducted in the previous chapter for the Orinoquia region for the year 2030. Consequently, the same three agricultural intensification scenarios (low, medium, and high) and the reference scenario evaluated in Chapter 4 are compared here.

The results indicate that in the process of continuation with the current inefficient management practices or with markedly less intensification of the current agricultural crop and cattle production, 26%–93% of the existing natural vegetation areas will be converted to agricultural land to meet the increasing food demand in the year 2030. This results in an increase of 53% (more than double) in the loss of biodiversity, as well as an increase of over 100% in the consumption of irrigation water compared to the findings reported for the year 2018.

Considering the medium and high scenarios, intensification enables satisfaction of an increased food demand within current agricultural lands and helps generate surplus land to produce energy crops, resulting in a reduction of biodiversity loss by 8% to 13% compared to the situation in 2018. Additionally, there is a benefit from bioenergy in terms of the efficient use of irrigation water. Despite increasing irrigation efficiency in more intensive production systems, the water demand for perennial crops and cattle production over the dry season increases significantly; thus, sustainable management practices that target efficient water use are warranted. For all scenarios, a positive net present value, between 120% and 690%, stemmed primarily from the intensification of cattle production and additional energy crop production.

Such a methodological approach helps provide more detailed knowledge on agricultural intensification, and low-ILUC-risk bioenergy production. This implies that the production of bioenergy on surplus land is assessed in an integrated manner. For this reason, the application of improvements in agricultural productivity, particularly for cattle production, is crucial for reducing the pressure on natural areas. However, this relies on targeted investments in the agricultural sector, particularly in the cattle production system, considering that the surplus land is derived from cattle intensification. Furthermore, it is extremely important to consider that an integrated planning of agriculture and bioenergy production is imperative for the region, particularly land use planning to distribute agricultural activities (i.e., crops and cattle) according to agroclimatic conditions, soil characteristics, and water supply to reduce potentially negative environmental impacts and to maximize yields. This is especially true for the flooded plain sub-region because this area is limited by restrictions for agriculture and cattle production intensification and will not be suitable for energy crops, considering its agroclimatic particularity.

6.4 Answers to the main research questions of this thesis

Research question 1: What are the environmental and economic impacts of different biomass production systems at national and regional level considering different management practices and land use scenarios?

The environmental and economic impacts of biomass production are diverse and depend mainly on previous land use, agricultural management practices, and the adopted production systems. The following five main environmental and economic aspects were analyzed in this thesis: i) land use and land use changes, ii) GHG emissions, iii) biodiversity, iv) water retainment, and v) economic performance. All aspects here are analyzed at regional level for three different crops (palm oil, sugarcane, and acacia) and different scenarios for 2030, while GHG emissions and economic performance were also assessed in more detail for palm oil at national scale for the current situation and for two future scenarios.

For the regional level analysis, Table 10 provides an overview of the changes in impacts on biodiversity, water retainment, GHG emissions, and economic performance in the Orinoquia region. The analysis was conducted for three scenarios of agricultural intensification (low, medium, and high) and a reference scenario based on the assumption of a business-as-usual development. The scenarios were compared with the situation in 2018.

Table 10. Key impacts of agricultural intensification and bioenergy production in 2030 for 4 scenarios compared to 2018 for the Orinoquia region. Op = oil palm, Sc = sugarcane and AC = Acacia.

Performance indicators	**Ref**	**Low**	**Medium**				**High**			
	Net agri-changes [a]	Net agri-changes [a]	Net agri-changes [a]	Net Bioenergy changes [b]			Net agri-changes [a]	Net Bioenergy changes [b]		
				Op	Sc	Ac		Op	Sc	Ac
LUC [c] (change in natural vegetation)	--	-	+	+	+	+	++	++	++	++
GHG emissions [d]	--	-	++	++	+	+	++	++	+	+
Biodiversity [e] (change in species abundance)	--	-	+	+/-			+	+/-		
Water use [f]	--	--	+/-	-	-	-	+	--	--	--
Net Present Value (revenue/ha)	+	+	++	++	+	+	++	++	+	+

Signs: The signs indicate an increase (+) or decrease (-) of the impact compared to 2018 where + positive change; ++ very positive change; - negative change; -- strong negative change; +/- negligible change.

***** High scenario. In this scenario it was included the potential of national indicators of the future oil palm production as a bioenergy crop evaluated in chapter 3 of this thesis.

Abbreviations: Op - oil palm; Sc - sugarcane; Ac - acacia; n.a - not applicable.

[a] Agricultural changes refers to the effects caused by food crops and cattle production.

[b] Bioenergy changes refer to the effects caused by energy crops production on surplus land from agricultural intensification., It is assumed that all surplus land in the Orinoquia region is used either for oil palm, sugarcane, or acacia, causing the same impact since there is no variation in the hectares used for energy cultivation. For the national level, oil palm crops are developed in the potential areas according to the land suitability map.

[c] Land-use changes are analyzed considering the cover type and agricultural area in 2018 conditions for the Orinoquia region, considering this year as the current situation. The percentage of surplus land is the relationship between the total agricultural area currently in use in the Orinoquia region (6.8 Mha) and the surplus land obtained from the intensification of that agricultural land.

[d] GHG emissions are evaluated based on the results of chapter 3 and 4.
[e] For biodiversity in the medium and high scenarios in the Orinoquia region, agricultural intensification contribute to an increase in species abundance mainly due to reducing the impact of increased cattle production and conserving biodiversity in natural vegetation assessed in chapter 5.
[f] Water use in agricultural production includes irrigation water for perennial food crops (i.e., plantain, cassava, oil palm for cooking oil) over the dry season. Moreover, it includes cattle water intake. In the medium and high scenario, water use for bioenergy considers irrigation during the dry season for the respective energy crops (i.e., oil palm, sugarcane, or acacia).

i) Land use and land use changes

Increase in crop yield is one of the strategies considered to mitigate (I)LUC and related GHG emissions. At national level, it was found that sustainable oil palm production could be obtained by combining the increase in current crop yields with the use of available agricultural land suitable for the development of the oil palm (see chapter 3). At regional level, the medium and high intensification scenarios generated positive results because it enabled the production of energy crops on surplus land from agricultural intensification (i.e., 0.6 Mha in the medium scenario and 2.4 Mha in the high intensification scenario). However, by the year 2030, if current inefficient management practices continue or if only a low intensification scenario is applied, 26%–93% of the existing natural vegetation areas of the Orinoquia region will be converted to agricultural land to meet the increasing food demand. In the Orinoquia region, only strong cattle intensification aids reduction of land pressure and facilitates less occupation of land to provide a considerable area for the production of bioenergy with a low risk of ILUC.

ii) GHG emissions

GHG emissions were analyzed at regional level for three different crops (oil palm, sugarcane, and acacia) and different scenarios for 2030. GHG balances were also assessed in more detail for palm oil at national scale for the current situation and for two future scenarios. For the current situation of the Colombian oil palm sector, the carbon footprint varied in a range between −47 to −1646 kg $CO_2eq\ t^{-1}$ CPO, with an average carbon footprint of −690 kg $CO_2eq\ t^{-1}$ CPO. The carbon footprint for future scenarios varied in a range between −822 to −891 kg $CO_2eq\ t^{-1}$ CPO. Note that in future scenarios, CPO is partly used for the production of biodiesel to replace fossil energy. Regarding total (positive) emissions of the CPO production chain (fertilization, LUC, POME, fossil fuel, electricity), for the current situation were 2324 kg $CO_2eq\ t^{-1}$ CPO while total emissions for future scenarios, where the palm oil production chain is improved, are reduced by 55% compared to the current situation (1031 - 961 kg $CO_2eq\ t^{-1}$ CPO). The sensitivity analysis showed that carbon stock values directly influence LUC emissions from current national oil palm production, contributing between 16% and 28% to the total emissions. To reduce the impact of LUC on the GHG emissions land with high carbon stocks should not be converted to oil palm, while conversion of low-carbon land to oil palm can help generate net carbon sequestration. Considering the land-use categories converted to oil palm and the carbon stock values assigned to those categories, LUC emissions ranged from 327 to 695 kg $CO_2eq\ t^{-1}$ CPO. In the palm oil sector, the key measures that facilitate to achieve the best GHG balances in the future are the reduction of LUC, POME, and chemical fertilization emissions.

By evaluating GHG emissions of agricultural intensification (food crops and livestock) in the Orinoquia region, a variation in emissions was observed according to the scenarios proposed. In the reference scenario, LUC emissions from agricultural intensification represent approximately 90% of the total emissions (fertilizer, fossil fuel, CH_4). In the reference scenario, the expansion of beef production is the main cause of LUC-related emissions (318 Mt $CO_2eq\ yr^{-1}$) due to the conversion of shrubland to degraded pastures (i.e., pastures with low nutrient levels). For food crops, the highest contribution to LUC emissions is associated with the expansion of rice and oil palm for food (8.9 and 5.8 Mt $CO_2eq\ yr^{-1}$, respectively) due to the conversion of shrubland to cropland. By considering any of the agricultural intensification scenarios (low, medium, and high), it can be inferred that LUC-related emissions decrease because of the reduction in the conversion of natural areas into agricultural areas. However, for the low intensification scenario, LUC-related emissions remain remarkably higher than those in the medium and high scenarios (191, 48, and 33 Mt CO_2eq yr^{-1}, respectively). This is because the conversion of shrubland to degraded pastures is necessary to meet the demand for beef production. Consequently, agricultural intensification results in up to 83% emission reduction in Orinoquia's agricultural sector in 2030 compared to a business-as-usual scenario, largely due to increasing productivity of cattle production and improvement of degraded pastures.

The GHG emissions of bioenergy, i.e., sugarcane-bioethanol, oil palm-biodiesel, and acacia-bioelectricity produced on surplus land from such agricultural intensification results in GHG emission reductions of more than 100% compared to their fossil fuel equivalent. Therefore, they meet the RED II GHG saving requirements, which is 65% for biofuels (i.e., bioethanol and biodiesel) and 70% for bioelectricity. Energy crops (perennial) grown on surplus land contribute to increasing carbon stocks in areas previously used for cattle grazing or degraded lands with very low carbon stocks, reducing emissions from land use. Net GHG emissions of bioenergy supply chains show that LUC-related emissions also dominate the GHG balance. The future expansion of energy crops should be performed in the current agricultural areas with low carbon stock and on surplus land from agricultural intensification to prevent deforestation and reduce (I)LUC-related emissions. An integrated perspective of agricultural land use will help enable the sustainable production of both food and bioenergy in terms of GHG emissions.

iii) Biodiversity

Agricultural intensification and bioenergy production may also result in biodiversity loss as it triggers changes in the landscape and species abundance Changes in biodiversity caused by changes in land use can be assessed using the mean species abundance (MSA) in a given area in both undisturbed and disturbed habitats. The impacts on biodiversity driven by LUC can vary across regions.

In the Orinoquia region, there are three diverse sub-regions in terms of the landscape, type of natural vegetation, and agricultural area occupation. For all scenarios proposed, the foothill sub-region demonstrated less impact on the species abundance, considering that presently, this sub-region does not possess an area of high natural vegetation that can be affected by agricultural expansion. In contrast, the high plain and flooded plain sub-regions exhibit a substantial impact on MSA due to the large area of natural vegetation compared to the foothill sub-region. This shows the importance of improving agricultural management in the agricultural areas that are currently in use. When intensification is considered, an increase in the MSA score value is observed; the value for the medium (0.8) and high scenario (0.8) is higher than that of the reference scenario (0.3). This is mainly attributable to the conservation of biodiversity in natural vegetation. Overall, in the Orinoquia region, projected LUC resulted in an improvement of the total MSA value by 8% to 13% for the medium and high scenarios, respectively, compared to the situation in 2018. Additionally, energy crop production on surplus land does not result in a loss of biodiversity due to the protection of the current natural vegetation areas of the region.

iv) Water

In the Orinoquia region, although approximately 90% of the water supplied to crops (annual and perennial) is derived from annual rainfall, during the four months of dry season, it is necessary to supplement with irrigation water to tackle the crops' water deficit. There are higher irrigation requirements for perennial food crops in the reference (5,524 million m^3 $year^{-1}$) than for the medium (2,670 million m^3 $year^{-1}$) and high scenario (1,485 million m^3 $year^{-1}$). There are additional irrigation water requirements from energy crop production for the medium scenario (3,154 million m^3 $year^{-1}$ for oil palm; 5,811 million m^3 $year^{-1}$ for sugarcane; 3,765 million m^3 $year^{-1}$ for acacia) and for the high scenario (7,663 million m^3 $year^{-1}$ for oil palm; 14,124 million m^3 $year^{-1}$ for sugarcane; 9,149 million m^3 $year^{-1}$ for acacia). It is important to note that in the high scenario more irrigation water for energy crops is needed than in the medium scenario due to the greater amount of surplus land available for perennial energy crops in the high scenario (2.4 Mha) than in the medium scenario (0.6 Mha). Thus, although irrigation water requirements per unit of biomass in the high scenario are lower than in the medium scenario, in absolute terms, more irrigation water is required. For the energy crops planted on the surplus land in the medium and high scenarios, sugarcane reports the highest consumption of irrigation water which is related to the crop's high transpiration rate.

The use of irrigation water for perennial food crops in the dry season increased by 111% in the reference scenario compared to the situation in the year 2018. However, the intensification scenarios exerted less impact on water sources than the reference scenario. The use of irrigation water for perennial food crops in the medium intensification scenario increased by 1% compared to 2018, while in the high intensification scenario, water use for food crops was reduced by 44% compared to the 2018 values. Thus, the high scenario showed better performance than the medium scenario because the irrigation system in the high scenario was more efficient than that in the medium scenario, thereby reducing water consumption. In addition to water use for food production, there is an increase in water demand for the energy crops grown on surplus land. In the medium scenario, less water is consumed by energy crops than in the high scenario because there is less surplus land for energy crop production

Direct water intake by cattle is quite small compared to the water consumption by crops. Indirectly, the animals consume grass/forage which also needs water to grow. The estimated water intake per animal for the reference scenario was 18.4 kg water day^{-1}, while this was slightly higher for the low (19.6 kg water day^{-1}), medium (20.5 kg water day^{-1}), and high (22.6 kg water day^{-1}) scenarios. Note that the water intake estimate is based on the consideration of the maximum temperature (27.9 °C) and relative humidity (80.4%) of the Orinoquia region; therefore, the water intake by cattle is increased to alleviate animal heat stress. Moreover, a greater consumption of dry matter in the diet of animals warrants greater consumption of water. Therefore, in scenarios where a higher cattle body rate is assumed, the dry matter intake ais higher e, resulting in higher water consumption per animal.

v) Economic performance

This aspect was analyzed at regional level for three different crops (palm oil, sugarcane, and acacia) for the current situation and for different scenarios for 2030. The economic performance of oil palm was also assessed in more detail at national scale for the current situation and for two future scenarios. Economic viability is a concern for the development of a bioenergy production business. In this regard, the net present value (NPV), internal rate of return (IRR), capital expenditure (CAPEX), and operational expenditure (OPEX) are considered the most representative indicators to assess. The assessment of the economic performance of the- Colombian palm oil sector in the current situation and for two future scenarios showed variation in CPO production costs. In the current situation, CAPEX was estimated at 38 USD t^{-1} CPO (51% POM costs and 49% crop costs) and OPEX was estimated at 519 USD t^{-1} CPO (14% POM costs and 86% crop production costs). The costs of processed fresh fruit bunches (FFB) are estimated at 125 USD t^{-1}. The NPV is estimated at 895 USD t^{-1} CPO, and project profitability at34% IRR. The economic performance varies according to the technological conditions of the production chain. CPO production costs are lower in future scenarios than in the current situation. This is due to the higher yield of the crop (30 t FFB ha^{-1} year^{-1}), the larger scale of the mill (70 t FFB h^{-1}), and cheaper feedstock (110 USD t-1 FFB) at the mill in future scenarios. Additionally, the estimated income of approximately 800 USD t^{-1} CPO is based on the expected sale of CPO (92%), power surplus (5%), and pellets (2%).

The economic performance of energy crop production at the regional scale was assessed based on a combination of agricultural intensification and bioenergy production on the resulting surplus land.

Agricultural intensification comes with increased profitability from cattle production and from bioenergy crop production; only small changes in the NPV occur due to changes in the economic performance of agricultural crop production. In the high intensification scenario, the NPV of cattle production increased substantially (2,757 USD ha^{-1}) compared to the reference scenario (102 USD ha^{-1}), indicating that economic benefits are higher in an intensive cattle production system than in an extensive cattle production system. The NPV of (increased) agricultural production in the region increased by 191% compared to the current situation (2018). Agricultural intensification increases output per hectare and allows for additional production, which increases revenue and NPV. In the medium and high intensification scenarios, a larger portion of agricultural land is available for energy crop production. The NPV of the reference scenario is between five and seven times smaller than the NPV of the high scenario with the production of any of the energy crops, that is, sugarcane, oil palm, or acacia. Sugarcane and acacia have comparable NPV's in both the medium (1,237 USD ha^{-1} for sugarcane and 1,579 USD ha^{-1} for acacia) and high scenarios (1,470 USD ha^{-1} for sugarcane and 1,978 USD ha^{-1} for acacia), but the NPV of oil palm FFB is higher than the other two energy crops in both scenarios (3,946 USD ha^{-1} and 5,306 USD ha^{-1} for the medium and high scenario, respectively). Given that the cultivation costs of oil palm (i.e., establishment, fertilizers, labor, harvest) are the same for both its use as food and for its use as bioenergy, the NPV of oil palm in the medium and high scenario is higher than all other food and energy crops.

In the Orinoquia region agricultural intensification contributes to increased profitability. Depending on the energy crop assessed and the scenario proposed, an additional 0.76 to 12.6 billion USD from energy crop production could be generated. The investment in energy crops demonstrates an IRR ranging between 14.6% and 18.7% at the regional level. Overall, the environmental and economic impacts and bioenergy potential differ per energy crop and per region depending on the future food demand and the potential for agricultural improvement. Environmental impacts caused by LUC can be mitigated and avoided if proper management of resources and agricultural practices are performed. Additional research is necessary on impact analysis in combination with a more detailed analysis of future bioenergy potential.

The evaluation of environmental and economic impacts at the national and regional level enables the identification of strategies to reduce the potential impacts of land use on biodiversity and water. Producing bioenergy on surplus land can positively impact biodiversity. Species abundance can benefit from avoiding the conversion of natural vegetation into agricultural lands. Although the impacts on water resources are limited, it is necessary to propose efficient water management strategies for perennial crops, especially over the four months of the dry season in the Orinoquia region. This is possible using efficient irrigation systems. Bioenergy production positively affect the regional economy by increasing the amount of agricultural commodities produced within the same agricultural area that is currently being used. The Orinoquia region can then benefit from the sale of biomass for the production of biofuels or bioelectricity. Additionally, by taking advantage of all the biomass generated both in the field and in the industrial area, the economic benefits can be higher. For the oil palm sector, additional income from the sale of electricity or new bio-based products such as, compost, or pellets can make the business even more profitable.

Research question 2: What are the key measures to improve the environmental and economic impacts of biomass production in the future?

For effective and sustainable development of the agricultural sector that also provides more sustainable biomass resources over time, a combination of measures and policies is warranted. Figure 10 shows the measures to improve the environmental and economic impacts of bioenergy considered in this thesis for evaluation at the national and regional levels. In Chapter 3, measures to improve the palm oil production chain were assessed at the national level. In Chapters 4 and 5 measures to increase agricultural productivity in the areas currently in use for agriculture are assessed at the regional level. Intensification may lead to the generation of surplus land that can be used to produce bioenergy with low ILUC risk, thereby minimizing the related impacts.

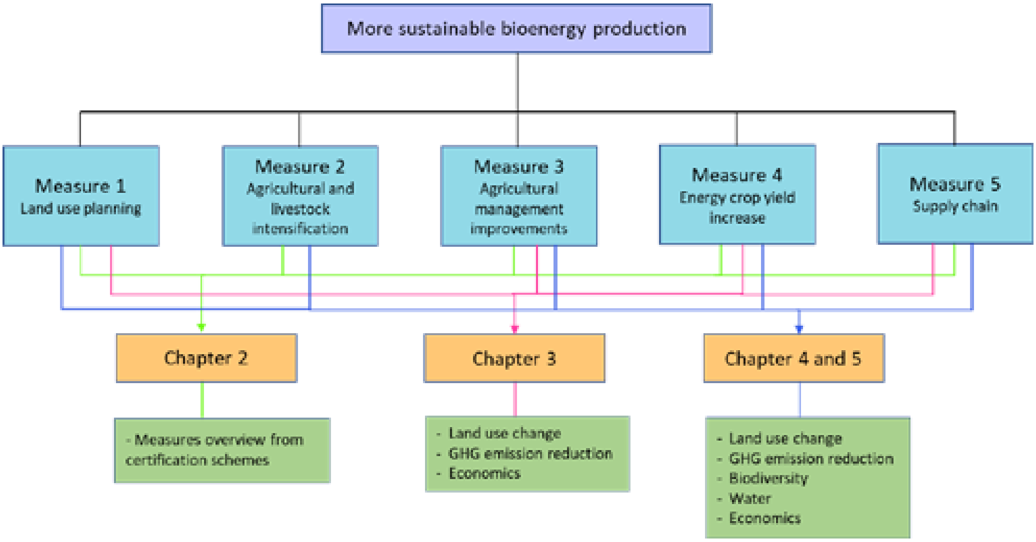


Figure 10. Overview of key measures to improve the environmental and economic impacts of biomass production in the future**.**

A coherent certification system is part of the measures identified in Chapter 2, and includes environmental, social, and economic issues of the bioenergy production chain. Certification schemes can be used by the private sector (to exclude producers who do not meet the criteria), with independent certifiers to assess a specific supply chain. However, the combination of effective monitoring and legal sanctions against companies that do not meet sustainability criteria is a model that can be adopted. The use of these measures was evaluated in Colombia's palm oil production chain. For example, it was identified that the possible costs of breaches of environmental law related to noncompliance with maximum permissible levels of contaminants in discharge from the mill could lead to the closure of the establishment for a week. Several certification schemes have included various approaches to categorize, select, and protect areas with high biodiversity and high carbon stock areas that should not be used for the development of the bioenergy sector.

Efforts have been engaged to include several sustainability indicators of bio-based products such as ILUC, water, biodiversity, and GHG emissions in certification schemes. For example, Directive (EU) 2015/1513 (REDII) prescribes a reduction in the risk of ILUC in biomass production. Although certification schemes have not included parameters defined for ILUC, some studies have reported that the risk of ILUC can be mitigated through the production of biomass on lands with low carbon reserves, lands that are no longer used for food and feed production, and on surplus land obtained from agricultural intensification. Another example is the development of criteria for the care and use of water. All sustainability standards recognize the need for water conservation from three points of view: availability, efficient use, and quality. In terms of efficient use, irrigation efficiency is generally used as an indicator., The economic areas of concern in certification schemes are related to economic viability, legal compliance, good management practices, and continuous improvement. The last two concerns are included in the economic area because the producers of biomass or bio-based products must maintain or improve the processes and conditions of their operations to reduce the use of resources (e.g., input materials, supplies, fuel, energy, water). Since the environment cannot be separated from the economy, the Colombian national government continues to promote a vision of climate finance that enables the incorporation of climate change in the economic and financial planning of the country. The existing legal framework includes instruments and incentives to favor public and private investments in mitigating GHG emissions climate change. However, to achieve effective financing to address climate change mitigation and adaptation measures, it is necessary for Colombia to strengthen other financial mechanisms regarding i) market allowances, ii) compensation fees for air emissions, iii) green bonds, and iv) access to mitigation and adaptation loans.

Another key component is the zoning of land use embedded in appropriate legal frameworks that highlights areas where agricultural production can occur and where it cannot. In this situation, the role played by national and regional governments is important because a combination of monitoring and sanctions is imperative for those who fail to comply with the established requirements. Furthermore, investments are warranted in the capacity building of farmers, livestock ranchers, and biomass producers (and their combination) to develop, implement, and scale-up improved cropping and agricultural management techniques for both food and bioenergy. For example, future national palm oil production chains must focus on emission reduction through the optimization of agro-industrial practices. This involves i) increasing crop yield, ii) reducing diesel consumption, and iii) adding value to residual biomass produced in the mills. In Colombia, the palm oil sector has the potential to produce approximately one million tons of lignocellulosic biomass per year. Implementation of good agricultural practices, such as planning the crop location (taking into account soil quality and water availability) and increase in the crop yield will be important to reduce land use-related emissions and CPO production costs.

Another improvement measure to minimize the effects of bioenergy expansion was evaluated at the regional level. Considering the current low efficiency in agricultural management in the Orinoquia region, agricultural modernization was proposed to increase food production in the areas currently used and to obtain surplus land that could be used for the production of energy crops. Using this approach, bioenergy is produced with a low (I)LUC risk and related GHG emissions, conforming to the latest international requirements for commercialization and use of bioenergy. It was identified that agricultural production could be improved and that chemical fertilizer use and their related emissions could be reduced. Similarly, diesel consumption in the field and its associated emissions could also be reduced. Furthermore, a combination of agricultural intensification and bioenergy production on the resulting surplus land can be a cost-effective strategy because it is possible to derive economic benefits from the sale of agricultural products, mainly related to beef, and extra profitability from energy crop products.

Research question 3: How can analytical frameworks be designed to facilitate the regional integrated assessment of land use and impacts of bioenergy scenarios and how can such frameworks strengthen governance for future sustainable biomass production?

The regional integrated assessment of land use and impacts of bioenergy production can be analyzed considering the use of methods that combine different analytical frameworks of sustainability for the production and use of biomass for energy purposes. In chapter 3, a full value-chain perspective of the Colombian oil palm was considered to analyze GHG emissions and economics. Chapters 4 and 5 use an integral methodological framework to investigate the effect of land use caused by the combined production of food and bioenergy on GHG emissions, water, biodiversity, and the economy of the Orinoquia region of Colombia. The methods were selected to allow for quick screening and assessment of future (and largely uncertain) developments in agricultural production for food and bioenergy and to accommodate limitations with respect to primary information and detailed data either for (sub) regional or national level. The implications of the integrated analysis of agriculture and bioenergy feedstocks, combined analysis of various impacts and scenarios, alternative methods, and data availability are explained below.

An integrated analysis of environmental and economic effects of the combined agricultural intensification and bioenergy production is needed to identify key measures to improve the impacts related to biomass production in the coming future. This type of integrated analysis facilitates the evaluation of several land use and impacts of bioenergy scenarios. However, analyses that address multiple environmental impacts and the economic performance at the same time are scarce in Colombia. But due to the limited access to the primary information required for robust analysis, it is necessary to use methods that can still provide an overview of impacts caused by LUC for different future scenarios.

This study linked different methods for the evaluation of combined food and bioenergy production including a comprehensive analysis of various impacts such as GHG emissions, water, biodiversity, and economy.

1) For GHG emissions, the most widely method used is the Life cycle assessment (LCA) methodology (ISO 14067). Emissions were calculated following IPCC 2019 Refinement guidelines. The calculation of the emissions was considered for each evaluated scenario. The emissions included LUC-related emissions and the emissions related to (annual and perennial) crop cultivation and beef production. The GHG emissions related to crop production include emissions of fertilizer production, fertilizer application, diesel usage, and methane (CH_4) emissions from rice production. The GHG emissions from beef production included emissions from feed production (CO_2 and direct/indirect N_2O; these emissions are calculated as for food crops), enteric fermentation (CH_4), and manure management (CH_4 and direct/indirect N_2O).
2) For biodiversity, the potential species richness index (MSA) was used as an indicator of regional biodiversity and it showed multiple benefits. However, the use of species richness alone as an indicator of biodiversity is often considered insufficient because it does not provide information on species' functional roles, contributions to ecosystem processes, and species composition. More precise quantification of the indicator requires data of original species abundance, which was not possible to obtain in the case of the Orinoquia region. The implementation of this index as a monitoring tool at local or even regional scales should include complementary indicators/metrics to properly capture the patterns of biodiversity loss in productive systems. Some of the indicators/metrics that could be used for this purpose are the Biodiversity Intactness Index, the Wildlife Picture Index, the Human Footprint Index, Ecosystem Integrity, or the Forest Health Index.
3) Regarding the soil-water balance, it provides a general idea to quantify the crop water needs; however, this method allows the equation to be simplified or made more complex depending on the available data. Although the Orinoquia region has a considerable number of public weather stations for data such as precipitation values, datasets are not complete because there are few or no updated reports on variables such as solar radiation, wind speed, and relative humidity. Despite this, the method can be used with limited climatic data. Advanced modeling methods can be applied to establish more specific interactions between climate, soil, crop genetics, and technical management of the area to optimize water use. The Soil and Water Assessment Tool (SWAT) can be used for sustainable water planning and watershed management. It is a reliable tool for predicting hydrological processes applicable to various climatic environments and hydrological flows.
4) For analyzing the economic feasibility, the most widely used method is the net present value (NPV) which is usually used for assessing the economic feasibility of individual alternatives or to compare among different alternatives to choose the one that brings the largest benefits. The NPV is used to evaluate present and future scenarios of food and biomass production at regional or national level. At regional scale, it was compared different intensification levels and their

implication. This study considers agricultural intensification as an investment portfolio at a regional scale and uses regional NPV aggregation because it preserves the relative feasibility of each intensification level.

The analysis of the impacts was conducted for different scenarios approach to understand different future possibilities and identifying preconditions to strengthens governance to regional or national scale. The scenarios considered different levels of agricultural intensification (crops and cattle) to evaluate the option of producing more on less land. In this way, free land could be used for bioenergy production with low ILUC risk. Using the scenarios approach and the combined analysis of the impacts it was possible to compare scenarios for agricultural intensification and bioenergy production in the Orinoquia region and thus obtain a general overview of the impacts driven by those sectors. Additionally, a combined assessment allows for obtaining an integral view of the regional impacts, given the time and resource constraints that could arise, and provides a description of the main impact categories to assess different future scenarios.

A key aspect of using a comprehensive analysis of various impacts is the possibility of focusing on an interim level of complexity to easily access the available information about the region because detailed information such as spatially specific data cannot be accessed. As it was mentioned before, the selected impacts i.e., biodiversity, water, GHG emissions, and economics, were quantified with specifically selected methods using available data that allowed a quick selection at the (sub) regional or national level as appropriate. Although more detailed and spatially explicit data and analysis, paths, and more refined methods for analyzing key impacts are possible and recommended, the combination of tools and methods presented in this thesis provides a foundation for delivering that knowledge. However, alternative methods for analyzing biodiversity, water, and economics are available. For example, i) for biodiversity, several indices have been proposed in the literature such as Biodiversity Intactness Index, Wildlife Picture Index, Human Footprint Index, Ecosystem Integrity, and the Forest Health Index, among others but these indices require more precise data from the region, but that is not available. ii) To assess water resources, some simulation models such as CropWat and AquaCrop allow the implementation of an agroclimatic alert system to support decision-making on alternative management technologies aimed at reducing the effects of adverse weather events. More robust models such as the soil and water assessment tool (SWAT) require high-quality input data to predict both the long-term impacts at the basin scale and the environmental impact of land use, soil erosion control, and non-point source pollution control. iii) For economics, complementary studies are required to reduce the risk associated with a financial investment given the uncertainty of the potential income. Indicators such as net income per ha, internal rate of return, and return on investment, land use competition, and macroeconomic indicators can improve the identification of the viability of an agricultural investment. Some economic models allow the analysis of economic links at the regional or national level, such as input-output analysis but this type of analysis requires a detailed input-output table not available for the Orinoquia region.

Considering data collection is crucial to reduce the uncertainties and to obtain more accurate results, in chapter 3, a full value-chain perspective of the Colombian oil palm was considered. The key to the emissions and economic analysis carried out in chapter 3 was the collection of primary data directly from the palm oil mills (field survey) to identify the potential for improvement in the production chain in terms of emission reduction and cost reduction. Regarding the total national production of fresh fruit bunches (RFF) in 2017, the data collection of 70% of the production of FFB was achieved for this study. However, at regional level, there was limited access to the primary information required for a robust analysis on the impacts driven by land use and several biomass production chains (sugarcane, acacia, oil palm).

6.5 Final remarks and recommendations for further research

The final remarks and key recommendations of this thesis are summarized in the following nine points.

1. Improving agricultural practices can be an effective strategy for reducing the pressure on natural land in Colombia. Particularly improving the efficiency of existing food crop production and closing yield gaps have the potential to reduce LUC and its related GHG emissions. Agricultural intensification is considered an important measure for making surplus agricultural land available for energy crop production, mitigating ILUC, and improving the GHG emissions of biomass value chains. The intensification of crop and cattle production may also contribute to improving the environmental and economic performance of the agricultural sector. The intensification of cattle production has been identified as a crucial option in Colombia to free land for other purposes, such as biomass feedstocks for energy production.

2. It is important to establish spatial planning of agricultural areas to consider environmental, social, and economic constraints. In Colombia, the zoning of agricultural, livestock, and forestry areas has been conducted to direct agriculture's expansion and to avoid deforestation. However, spatial planning is needed at a local scale to avoid the use of areas with natural vegetation that currently have a high carbon stock, such as some areas of natural savanna in the Orinoquia region. Moreover, spatially explicit data and analysis are key tools for evaluating and monitoring environmental and socioeconomic aspects related to agricultural production. For example, including soil carbon content and ecological restoration processes in more advanced, spatially-specific LUC models could allow more precise projections on the location and availability of areas for agricultural or biomass feedstock production without negative impacts related to LUC. This, in turn, could be used for improved future land use planning and zoning in Colombia and in different regions of the country.

3. More research needs to be conducted to evaluate the environmental and economic performance of biomass production for energy and materials in Colombia. This thesis has emphasized the need for generating local, primary data on particularly biodiversity, land use, and water consumption. For example, although Colombia's agricultural areas are demarcated for specific zones in order to limit expansion to only certain areas, a detailed map with information on and location of currently used areas, including land use category, has not been updated since 2010. At the moment, regionally or locally-specific data are often insufficient to be used in the analysis, while there is uncertainty about land availability in specific area of the country, such as the Orinoquia region. For example, for water depletion, more advanced and robust methods such as the SWAT are available to assess water resources, but the required local, high-quality input data is not available. In addition, the integrated approach to evaluate the impacts of land use and different management options on natural resource use, such as crops, livestock, soils, water, and biodiversity could provide a comprehensive understanding of ecosystem services and functions. Using accurate local primary data in such an analysis can reduce the uncertainty in the results, which is important especially in areas as sensitive as the Colombian tropics and the Orinoquia floodplains.

4. Agricultural intensification as a proposal to minimize pressure on land use and increase the current productivity needs more research to define strategies for its implementation in Colombia. For example, the specific areas where it is already applied or where it could best be applied may not have been established. Likewise, it is necessary to propose and implement government strategies to benefit and stimulate the agricultural sector. This may include economic incentives for decarbonizing agricultural production, such as incentives for soil improvement, increased carbon stock, reduced chemical fertilization, and increased organic

fertilization. Another government strategy can help provide greater support for research and development in the country's agricultural sectors. Additionally, the government can encourage the employment of personnel trained in management and improvement tasks for agricultural production.

5. Socio-economic issues represent another area that requires the use of both advanced evaluation methods and accurate data. In Colombia, the analysis and monitoring of socio-economic impacts of LUC, zoning policies, investment in rural areas, and modernization of agriculture and livestock should be expanded and deepened. However, this requires more detailed data and more advanced tools (e.g., input-output analysis and computable general equilibrium models) as well as other methods that can map social impacts and relevant development indicators.

6. The analysis and implementation of the potential for sustainable biomass production is closely linked to mitigation strategies of the national government to reduce GHG emissions in all economic sectors of the country. Bio-based economy is a developing sector in Colombia, and biomass plays an important role in mitigating land use. A combined analysis with energy models is desirable for optimal implementation of bioenergy. This type of analysis can be conducted using methodologies such as a hybrid statistical balance and land suitability allocation approach to produce energy crops.

7. Although Colombia is ready to embrace a sustainable bio-based economy, it continues to counter challenges such as the implementation of and compliance with all laws that have been established in recent years in the country. In addition to continuing to develop government incentives to promote the use of bio-based products and to use appropriate sustainability indicators (e.g., LUC, ILUC, food security), it is important to establish trust through good governance and inclusion of sustainable markets, better monitoring, and sanctioning mechanisms if activities or actors do not follow the laws.

8. This study highlights that the application of regulatory frameworks and voluntary certification schemes can strengthen national governance for sustainable biomass production. Companies committed to sustainable production can be certified by either private or public certifiers and meet the established requirements. Governments must issue and comply with the requirements of public policies that make bio-based products sustainable in countries such as Colombia, where a bioeconomy is being developed to strengthen the national and regional economies. The Colombian government promotes the vision of climate finance. This vision allows for the incorporation of climate change into the economic and financial planning of the country. In this way, it encourages public, private, and international cooperation via financial resource flows for the adaptation and mitigation of climate change. However, to achieve effective financing to address climate issues, it is necessary for Colombia to strengthen other financial mechanisms regarding i) market allowances, ii) compensation fees for emissions, iii) green bonds, and iv) access to mitigation and adaptation loans. Although the government has already generated some tax, tariff, and accounting incentives for investment in and the use of renewable resources (solar, wind, biomass), only 2% of the country's total energy generation corresponds to biomass cogeneration. Therefore, there is substantial potential for continued and increased investments in the country's energy sector involving the use of biomass.

9. The use of sustainability indicators and frameworks for monitoring, analysis, and control of sustainable biomass production combined with the implementation of better management of food crops and livestock at the local scale is highly desirable. For this, a combination of measures and actions can be carried out at the national level, such as i) the mandatory application of recognized sustainability standards for the production of biomass for energy and material

purposes. ii) Greater and better monitoring of the impacts of the production and use of bio-based products is necessary. iii) Developing legal actions to establish fair trade through regulations that benefit workers and producers in relation to wage regulation and protection of the environment. iv) Expand the commercialization of bio-based products both in the national and international territory.

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Curriculum Vitae

Nidia Elizabeth Ramírez-Contreras completed the BSc program Food Chemistry at Universidad Padagógica y Tecnológica de Colombia (2001) and the MSc program Environmental Management at Pontificia Universidad Javeriana (2015). During her master's studies, she specialized in biochar production to reduce water contamination in palm oil effluents.

At the end of 2016, Nidia started her PhD research at the Faculty of Science and Engineering (FSE) at the University of Groningen. Her research was part of the bilateral project BBE Colombia-NL: "Towards a long-term science and innovation collaboration between Colombia and the Netherlands in Biomass Valorisation" (RVO TF13COPP7B). The research focused on the evaluation of the environmental and economic performance of biomass production for energy and materials in Colombia and defining strategies to work towards more sustainable production of biomass. In addition, in the last decade, she has worked as a researcher in the palm oil production process with an emphasis on the use of biomass for the generation of bioenergy and other bioproducts.