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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 8–13% 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.

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%

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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, 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.

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 (Fig. 1) 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, high-plain, and foothill of the Orinoquia region (section 1A in Supplementary Material describes the geography, economic activities, characteristics of climate and biodiversity, and the various subregions in more detail).

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

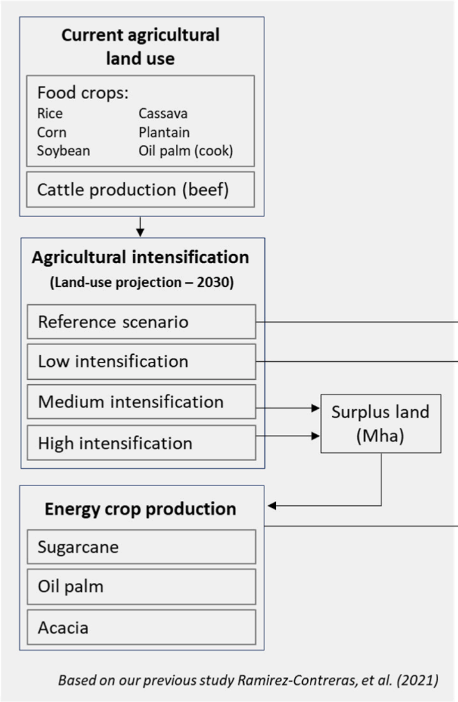

Fig. 1. *Overview of the environmental impacts and economic performance of agricultural intensification and energy crop production at subregional level. The light gray area is part of the analysis based on the results of our previous study* (Ramirez-Contreras et al., 2021) *where the LUC projections for the Orinoquia region in 2030 was obtained.*

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 1) 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 A1 in Supplementary Material). 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 1
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] The 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 Supplementary Material 2 A.

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

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 A2 in the Supplementary Material). 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 (1). We then calculated the net MSA change by comparing the intensification scenario to the reference scenario.

$$MSA_{LU} = \frac{\sum_1^n (MSA_x * A_x)}{\sum_1^n A_x} \tag{1}$$

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 1.

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.

2.3.1. 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 (2). 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 Supplementary Material 4.1 A). Then, the available water holding capacity in these soils was estimated considering the methodology by USDA-NRCS (2004a) (*Equation A-4* and Table A7 in Supplementary Material).

$$\begin{aligned} WB_x &= \sum_{i=1}^{12} (EP_i - ETc \pm \Delta d) \\ ET_c &= \left(ET_{0i} * Kc_{i,x}\right) \end{aligned} \tag{2}$$

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-1* in Supplementary Material. 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 Supplementary Material). Data of monthly average precipitation (Table A3 in Supplementary Material) 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 Supplementary Material 4 A).

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 A4; Table A5 in Supplementary Material). The crop evapotranspiration (ET_c) for specific plant material is calculated by multiplying ET_0 by the crop coefficient (Kc) (equation (2)). The Kc values were taken from Allen et al. (2006) assuming the Kc value of the medium crop development stage as shown in Table A6 in Supplementary Material. 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 (2). Then a weighted average of ET_c for all crops based on the land area of each crop is determined.

2.3.2. 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-5* and *Equation A-6* in Supplementary Material. 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 A8 in

Supplementary Material. 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.

2.3.3. 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 (3)). 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 A9 in Supplementary Material). The data for cattle land-use projection were taken from Table 1. 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.

$$WI = 9.449 + 0.190{*}MBW + 0.271{*}\ T_{max} - 0.259{*}HU + 0.489{*}DMI \tag{3}$$

Where, WI = water intake (kg day^{-1}); MBW = metabolic body weight or live weight in $\text{kg}^{0.75}$ (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}).

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 (4). 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).

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+i)^t} \tag{4}$$

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 A13 in Supplementary Material). 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 A11 in Supplementary Material. 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 Supplementary Material 5 A.

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 Fig. 2). 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).

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 (Fig. 3). 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 A2 in Supplementary Material). 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 Fig. 3).

3.2. Water

3.2.1. 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 Fig. 4). 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 Supplementary Material) 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.

Regional needs for supplementary irrigation water for perennial crops for both food and energy over the dry season are presented in Table 2. 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 A8 in Supplementary Material). 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 2 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 2). 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.

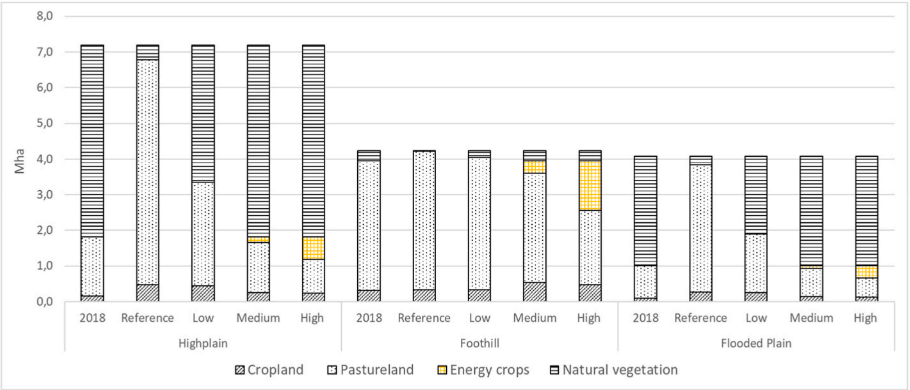

Fig. 2. Projected land use and distribution by type of land use for three subregions and different scenarios in 2030 compared to 2018.

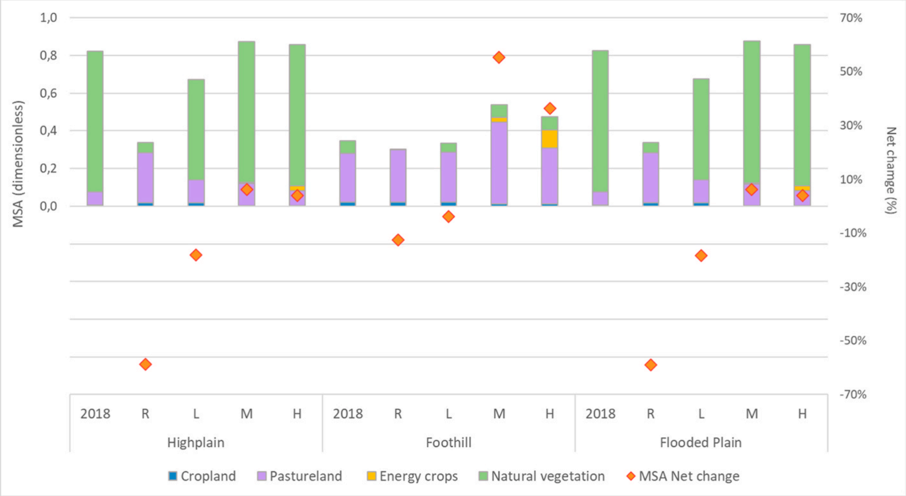

Fig. 3. Total MSA by subregion and scenarios. The net MSA change is the percentage of change of the MSA values of the reference (R) and intensification scenarios (L - low, M - medium, H - high) with respect to 2018. For the medium and high scenarios, no distinction between the energy crops is made because the assigned MSA_{LU} value is the same for all (see Table A2 in Supplementary Material).

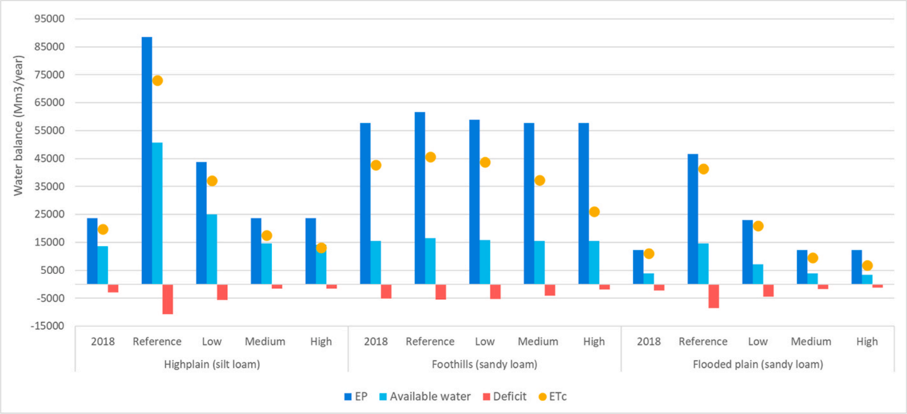

Fig. 4. Annual soil-water balance for all crops by scenario and subregion. EP = effective precipitation (i.e., the fraction of the total precipitation that is actually used by crops to satisfy water needs; for each subregion, EP is related to the agricultural area by scenario to show the annual value 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.

Table 2

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	1255	136	554
Reference	Food-crop[a]	534	2539	310	1324	421	1724
Low	Food-crop[a]	494	2352	308	1316	393	1856
Medium	Food-crop[a]	228	825	505	1294	216	551
	Oil palm[d]	258	942	608	1567	253	645
	Sugarcane[d]	508	1756	1198	2938	436	1117
	Acacia[d]	319	1150	486	1854	207	761
High	Food-crop[a]	258	461	448	717	224	307
	Oil palm[d]	1307	2289	2364	3807	1158	1567
	Sugarcane[d]	2278	4268	4659	7140	1869	2716
	Acacia[d]	1543	2794	1888	4506	977	1849

[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.

Moreover, since the irrigation water requirements are affected by the efficiency of the irrigation systems assumed in the scenarios (Table A8 in Supplementary Material), 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.

3.2.2. 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 °C; 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 A14 in Supplementary Material).

For each subregion, cattle water intake (Table A14 in Supplementary Materials) and the area dedicated to cattle varies (Fig. 3). 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 (Fig. 3). 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.

3.2.3. 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 5600 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 2). 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 15,600 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.

3.3. Economic performance

Agricultural intensification increases the yield of food crops and cattle and, as a result, their profitability (see Fig. 5). 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 and 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 Supplementary Material). 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 Supplementary Material). 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 (2853 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 (2846 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 Supplementary Material where it is highlighted that NPV of oil palm fruit and sugarcane are extremely sensitive to changes in market prices.

3.4. Regional impacts of agricultural intensification & bioenergy production

The results for the whole region are summarized in Table 3,

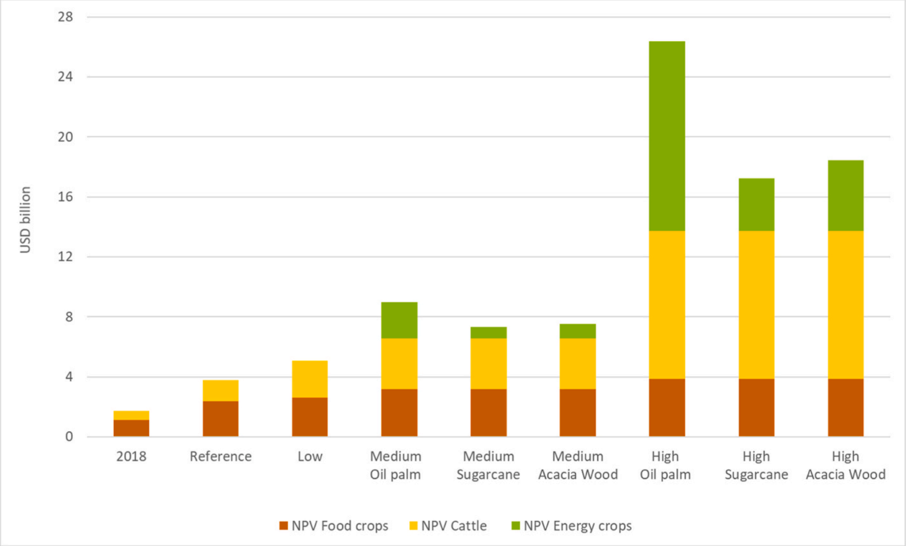

Fig. 5. 5Regional net present value by scenario for food crops, cattle, and energy crops.

Table 3
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[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).

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 Fig. 3). 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 8–13% 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).

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.

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., 2018, 2019). 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).

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.

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 Supplementary Material). 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. 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.

Author contribution statement

Term Definition.

Conceptualization This publication is part of a PhD thesis at the University of Groningen - the Netherlands. Therefore, the schedule and all the details which include goals and aims were proposed in the TSP (training and supervision plan) approved by the Graduate School of Science.

Methodology The methodology included the analysis of both agricultural intensification and bioenergy production in the Orinoquia region of Colombia, using globally recognized sustainability indicators. The calculations of the indicators were carried out in Excel.

Software Not applicable.

Validation Each of the co-authors actively participated in the development of the project, in the review and analysis of results.

Formal analysis The formulas of the indicators evaluated in the study were used.

Investigation Data collected using information from our previous study in the region, data from the linear programming model developed by Fontanilla-Díaz et al. (2021), who is one of the coauthors of this study, regional meteorological data, and literature.

Resources Not applicable.

Data Curation All the data collected along with the calculations made are kept in excel files for its use and later reuse.

Writing - Original Draft The paper was written directly in English by the main author with the help and constant monitoring of the co-authors. During its execution, the language edition was carried out.

Writing - Review & Editing During each stage of the project development, feedback from the co-authors was received.

Visualization All co-authors participated in the data presentation.

Supervision Dr. Professor **Andre Faaij** had the leadership responsibility for research activity planning and execution.

Project administration Dr. Professor **Andre Faaij** was responsible for managing and coordinating the planning of research activities. The PhD student **Nidia Ramírez** carried out the research.

Funding acquisition Dr. Professor **Andre Faaij** and Dr. **Jesus Garcia-Nuñez** were responsible for acquiring financial support for the project leading to this publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.114137.

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