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Bioenergy potential from invasive alien plants: Environmental and socio-economic impacts in Eastern Cape, South Africa

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ABSTRACT

South Africa's natural resources and ecosystems are negatively affected by Invasive Alien Plants (IAPs). We used a life-cycle approach to assess the environmental and socio-economic impacts of using IAPs for electricity generation in South Africa or exported and used for electricity generation in the Netherlands. Supply chain greenhouse gas (GHG) emissions of electricity from IAPs pellets, excluding land use change-related GHG emissions, are 31.5 $gCO_2eq\ MJ^{-1}$ for electricity generation in South Africa and 31.2 $gCO_2eq\ MJ^{-1}$ for electricity generation in the Netherlands. An additional 3.9 $gCO_2eq\ MJ^{-1}$ is accounted for if emissions of land use change are included and land is rehabilitated to its natural state. The removal of IAPs results in water savings when considering any potential land use transition, ranging between 1,263 mm $year^{-1}$ for annual cropland to 12 mm $year^{-1}$ for dense forest. The supply chain costs of pellets are 5,344 ZAR Mg^{-1} (285 € Mg^{-1}) delivered at the power plant in South Africa and 2,535 ZAR Mg^{-1} (159 € Mg^{-1}) delivered at Rotterdam port. Direct full-time jobs generated from removing IAPs up to the conversion-factory-gate are 604 FTE $year^{-1}$ for South Africa and 525 FTE $year^{-1}$ for the Netherlands. There are clear trade-offs between environmental and social benefits and costs. There are generally net carbon losses when considering the land use transitions after IAP removal, even when land is rehabilitated to its natural state. Using IAPs for electricity can be a valuable strategy for South Africa to generate employment, conserve water resources and reduce GHG emissions.

1. Introduction

To reduce the risk of serious impacts from climate change and avoid a temperature rise of more than 2 °C compared to preindustrial levels, deep greenhouse gas (GHG) emissions reductions are required [1]. For developing countries, such as South Africa (SA), reducing GHG emissions is challenging, as these countries also face other urgent development goals, e.g. reducing poverty and inequality [2]. South African energy supply is still dominated by coal for electricity generation, contributing approximately 85% to national GHG emissions [3]. In addition, SA is the 12th largest GHG emitter globally, with 434.5 Tg of CO_2 emitted in 2020 (from the consumption of oil, gas and coal for combustion), equivalent to 7.6 Tg CO_2 per capita (37th globally) [4]. Nevertheless, SA aims to maintain current GHG emission levels and not surpass the limit of 614 Tg of $CO_2eq\ year^{-1}$ before 2030; after 2030, SA has planned to reduce GHG emissions to 212 Tg - 428 Tg of $CO_2eq\ year^{-1}$ by 2050 [2]. To meet SA's and global GHG emission reduction targets, the development and deployment of renewable energy is crucial. Despite that photovoltaics and wind are expected to dominate the contribution to renewably energy [3,5], biomass is also expected to play an essential role in reducing the country's high coal dependency and meeting GHG emissions reduction targets [6].

The potential biomass supply for energy purposes in SA is currently limited and consists mainly of residues from agriculture and forestry [7]. Other biomass sources, such as IAPs, are recognized as promising feedstock. The use of IAPs for bioenergy could potentially result in carbon savings and, at the same time, deliver additional environmental and socio-economic advantages [8,9]. Invasive alien tree species such as pine and wattle (acacias) limit water availability [10]. Compared to the natural landscape (e.g., savannah/grasslands), these IAPs increase transpiration and evaporation losses and are characterized by a deep-rooted system that allows them to access deeper stored soil moisture [10]. It is estimated that IAPs reduce the country's water availability by 4% and without eradication measures, this can potentially increase up to 16% [11] and thereby aggravate droughts. For SA, this is a significant impact as the country has experienced an increase in the

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intensity of drought spells, leading to water crisis episodes in the last years [12]. In addition, the intensity and frequency of these extreme droughts are expected to increase further, driven by climate change [13]. Eradicating IAPs also benefits biodiversity as it helps protect and restore natural areas of endemic ecosystems such as the fynbos shrublands [14]. Removing IAPs has been a key priority since the introduction of the 'Working for Water' program (1995), which led to the treatment of more than 25,000 km^2, creating more than 250,000 direct jobs in the process (up until 2017) [15]. Despite the potential benefits of job creation, water source protection, and other ecosystem services, only a relatively small proportion of the estimated invaded area has been treated [14]. Approximately 114,000 ha of invasive alien trees have been submitted to initial treatment. However, it is estimated that invasive trees have invaded more than 1 million ha, and many species are now entering a phase of exponential growth [15,16]. It is estimated that IAPs could supply 11.3 Tg of solid biomass annually in SA [7]. However, this biomass source is currently largely underutilized as a result of logistical limitations [17]. After clearing, most of the IAP biomass is left on-site and therefore, potential valuable opportunities to use IAP biomass are wasted [9].

Using IAPs for energy purposes has emerged as an important sustainable development strategy to mitigate GHG emissions from non-renewable energy sources, protect the country's water resources, create job opportunities and protect biodiversity. Yet, such a strategy's success will rely largely on biomass availability, supply chain costs (including IAPs clearing and transport), benefits for water availability, and GHG emission savings. So far, IAPs assessments are generally targeted to biomass availability or biomass utilization costs (mainly focused on IAP's clearing) [6,7,18–21]. Few studies analyze the entire supply chain on utilizing IAPs for energy purposes [7,9]. Generally, the costs of using IAPs for bioenergy are high because of challenging logistics. Therefore, using IAPs is only feasible when subsidies are provided [17]. However, using IAPs for electricity generation can result in significant GHG savings. Net GHG savings between 69 and 250 g CO_2eq MJ^{-1} can be achieved compared to fossil counterparts (coal-dominated electricity) and excluding carbon stock changes from Land Use Change (LUC) [7]. Nevertheless, when LUC-related GHG emissions are accounted for, these net GHG emissions savings can be substantially reduced if a net carbon loss occurs, given the difference in carbon storage between IAPs and subsequent potential land uses (e,g., rangeland). Studies on the effect of IAPs on water availability have been limited to water savings/runoff from IAPs eradication [10,21–23]. For employment generation, only direct jobs related to the eradication process are generally accounted for. Therefore, a more integrated approach that includes important aspects such as LUC, water impacts, job creation, and supply chain costs is necessary to understand the overall environmental and socio-economic impacts and trade-offs from using IAPs for energy production. Such integrated assessment can support the development of the bioenergy sector in SA and assist efficient biomass use. Furthermore, it can contribute to meeting SAs GHG emissions reduction targets, job creation (poverty alleviation) and protection of water resources.

The main goal of this study is to assess the environmental and socio-economic impacts of using biomass from IAPs for electricity generation in SA. An international supply chain was also considered for comparison purposes, in which biomass is exported and used for electricity generation in the Netherlands (NL). The Netherlands was selected as it is one of the main importing countries of wood pellets [24]. Furthermore, Dutch biomass imports are projected to continue growing to meet domestic bioenergy demand [25,26]. This study assesses the socio-economic and environmental impacts of different landscape restoration scenarios. This study focuses on the Eastern Cape province of South Africa, as this province has the highest IAP biomass potentials in SA [7].

2. Methods

The environmental and socio-economic impacts of using IAPs for bioenergy were assessed following an integrated modelling approach that considered the social, economic and environmental context of the Eastern Cape province in SA. The following processes were included in the assessment: biomass harvesting/eradication, logistics and conversion, and land restoration after IAPs removal (taking into account local biophysical characteristics). This approach considers the potential environmental and socio-economic impacts that differ considerably for different IAPs species and successive land uses.

2.1. Scope and scenarios

To quantify the environmental and socio-economic impacts of the biomass supply chains and ensure the comparability of results, each assessed system must serve the same function. Electricity generation is considered the main end-use function. We divided the assessment into three steps (see Fig. 2).

Scope 1: Currently, the eradication of IAPs is limited. When land is cleared, biomass is left on-site, used for fuelwood by the local communities, or sold to timber companies [9]. Regardless of the final use, IAP clearing is set to continue in line with the Working for Water program. Therefore, the first step of the assessment focuses on assessing the impacts of land use transitions when IAPs are cleared and the land is rehabilitated. In this step, the scope is limited to only LUC-related impacts. Different successive land use scenarios are included after IAPs are removed (see Fig. 2 and section 2.1.4). This is done to consider and compare the potential impacts of different scenarios for landscape restoration. Indirect effects along the supply chain, such as indirect LUC-related GHG emissions are not considered. For example, nitrous oxide emissions from fertilizers when land is dedicated to agriculture after IAPs eradication.

Scope 2: In the second step, the scope is expanded to include the impacts of using biomass to produce wood pellets. For this step, the system boundaries cover all stages: biomass extraction (IAPs clearing and collection), debarking/chipping on-site, forwarding and transportation to the pellet plant, and pelletization. Therefore, the second step focuses on the impacts of producing wood pellets, excluding LUC impacts.

Scope 3: For the third and final step, the conversion to electricity is considered. This step compares the implications of generating electricity from IAPs pellets in SA or exporting pellets for electricity generation in the Netherlands. The analysis of water savings is limited to scope 1 (LUC-related impacts), as water use in the rest of the supply chain (steps 2 and 3) is marginal [27]. The overall results of the supply chain GHG emissions (scope 3) are presented with and without LUC-related emissions. For the supply chain costs and job creation, LUC effects are excluded.

2.1.1. Geographical scope

For the analysis, we focus on Port Elizabeth and its surroundings. We selected Port Elizabeth as it has an existing wood pelletization plant with a 120,000 Mg year-1 capacity. It also has access to two large operational harbours: Port Elizabeth and the recently built Port of Coega. Both have the required facilities for bulk export. The geographical scope was established by accounting for the service area (see section 2.1.3) required to meet the annual biomass demand of the pellet plant (biomass availability). This service area partially covers the municipalities of Kouga, Sundays river valley, and Nelson Mandela bay (see Fig. 1).

2.1.2. Temporal scope for impacts

GHG emissions other than CO_2 (CH_4 and N_2O) are expressed in CO_2 equivalent (CO_2eq) for a global warming potential (GWP) impact calculated over 100 years (GWP100) consistent with the characterization factors used in the directive on the promotion of the use of energy

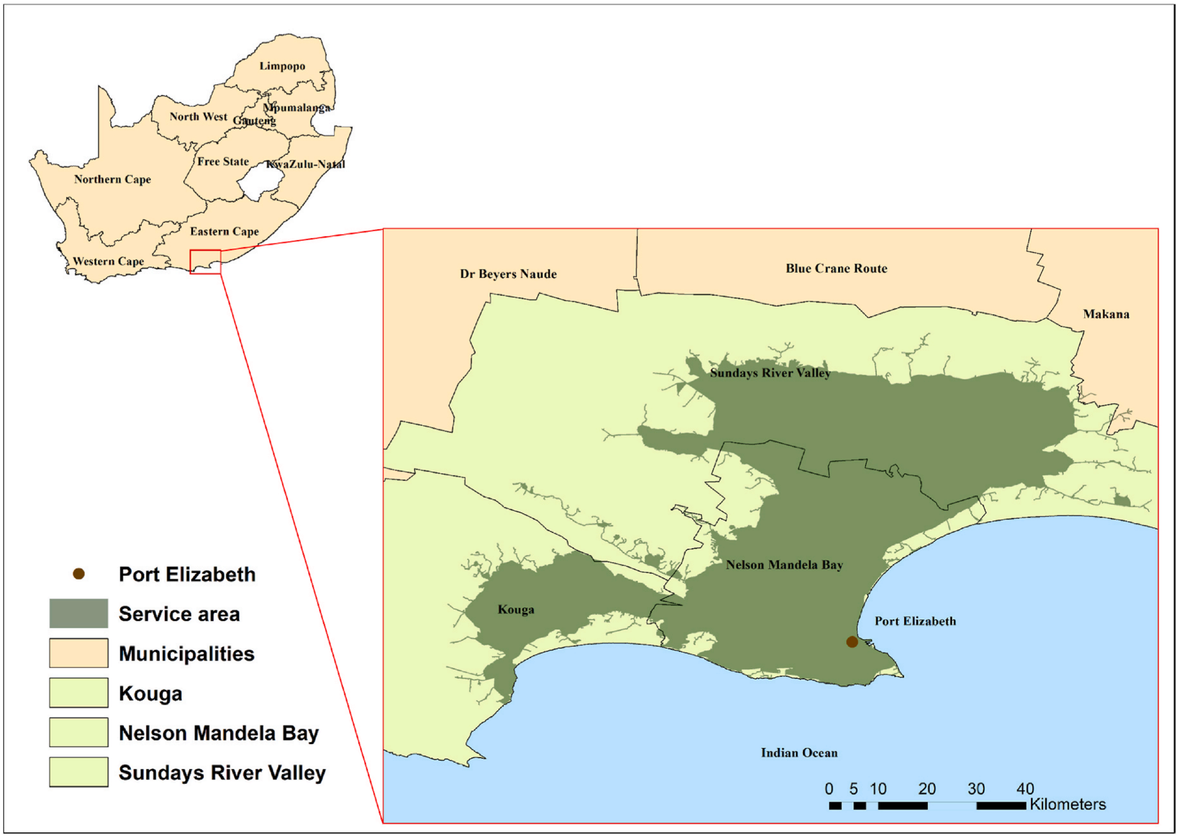

Fig. 1. The geographical scope of the study. Map of South Africa with the selected focus area in the zoom-in section.

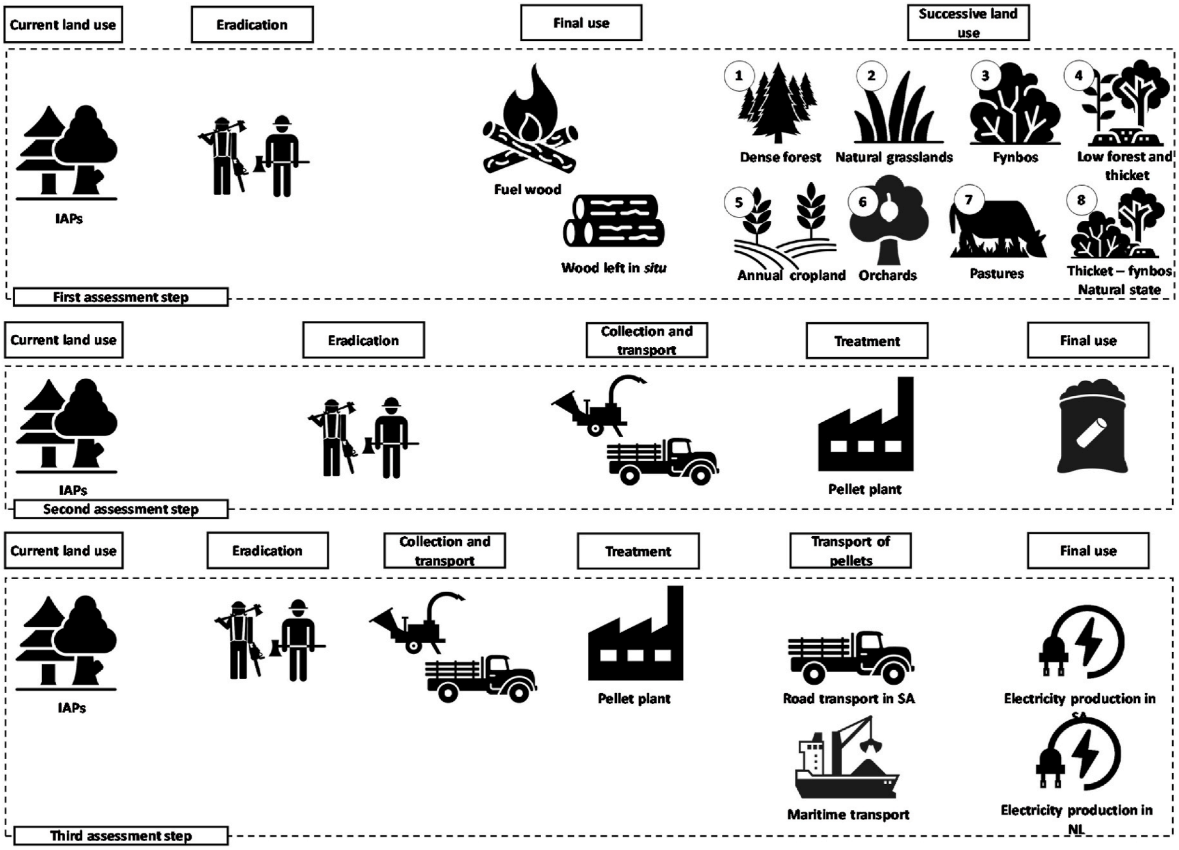

Fig. 2. IAP Supply chain scenarios and assessment stages.

from renewable sources recast (REDII) [28]. In addition, it is required to account for the different time horizons related to each environmental impact or process. For example, annual soil carbon fluxes from LUC are assessed for a 20-year horizon as it is assumed that it takes 20 years for carbon pools to reach equilibrium [29]. For water and socio-economic analysis, all parameters are assessed on an annual basis. The temporal effect of the different parameters is presented in each subsection.

2.1.3. *Availability, type and distribution of IAPs*

The availability and type of IAP that is eradicated and used for bioenergy largely affect the environmental and socio-economic impacts. This study focused on invasive trees since they offer higher biomass potentials than other invasive plants types in SA [7]. Woody biomass potentials were derived from South African Bioenergy Atlas [7]. This data set provides spatially explicitly the annual amount of standing (i.e. total) and exploitable woody biomass available per polygon (without species composition) for a 20-year time period. We used the exploitable woody-biomass potentials for this study, which refers to the amount of available biomass suitable for pelletization given its typical mass, age, and ease of access. Exploitable woody-biomass potentials are given in reference to the area of each polygon and available biomass is relative to the biophysical characteristics of each polygon (e.g. terrain conditions such as slope). The service area was estimated through a spatially explicit approach (GIS tools) based on exploitable woody biomass potentials, local infrastructure (i.e., roads) [7] and annual pellet demand. Therefore, the service area (Fig. 1) represents the optimized aggregated distance required to supply sufficient biomass to meet the annual demand of the pellet plant located in Port Elizabeth.

Given the lack of high-resolution data, the tree species composition was estimated by overlapping the inventory data on cleared sites in SA [30] with the service area. Accordingly, in previously cleared sites within the service area, the invaded areas were dominated mainly by acacia (68%), eucalyptus (13%) and pine (12%), and other species (7%). Given their minimal share, these other species are not considered in the assessment. To determine the cover dominance, we assumed that one unit of area is dominated only by IAPs. This approach is generally followed by similar studies in which one unit of area (e.g. hectare) is assumed to be covered 100% by IAPs (“condensed” area) [31–33]. Therefore, we assumed that one unit of the (“condensed”) area covered by IAPs is dominated only by acacia, eucalyptus and pines. We extrapolated the dominance shares found with the overlapping exercise to assume an IAPs distribution of 73% acacia, 14% eucalyptus and 13% pine.

2.1.4. *Post-removal land use scenarios*

The different land use scenarios after IAPs removal are based on [9, 34,35]. It is suggested that after IAPs removal, the cleared land could be restored to its natural state or used for agriculture and, therefore, recover and/or provide different ecosystem services [9]. It is assumed that after eradication, there is no regrowth of IAPs. We carried out two overlay exercises to identify the potential land use transitions after removing IAPs. First, we overlayed the most recent (2018) SA land cover data [34] with the service area. Second, we overlayed the SA vegetation map [35] with the service area. The vegetation data set provides the spatial distribution of vegetation classes in line with the country’s bioregions and provides vegetation groups with similar biotic and abiotic features.

The composition of land cover within the service area is predominately characterized as dense forest & woodland (26%), natural grasslands (20%), fynbos (7.8%), contiguous low forest & thicket (7.1%), annual crops (7%), cultivated orchards (3.8%) and fallow land (3.1%) used as pastures [34]. Accordingly, seven post-removal land use scenarios were considered for the assessment: Dense forest, natural grasslands, fynbos, low forest and thicket, annual cropland, orchards and pastures. Citrus crops, grains/cereals (dominated by barley) and grasses are the main crops produced in Kouga, Sundays river valley and Nelson Mandela bay localities [36]. Hence, for the orchards land use scenario, we assume the production of citrus crops and for the annual cropland scenario we assume the production of grains/cereals (barley). For simplicity reasons and a lack of high-resolution data on the exact location of invaded areas, we assumed that any land use transition scenario could occur after IAP removal if the local biophysical conditions are adequate. All the scenarios are assessed individually.

The composition of vegetation classes according to biotic and abiotic features within the service area is mainly characterized by the thicket (56%) and fynbos (33%) [35]. The remaining share is a combination of vegetation with large shares of natural grasslands. Therefore, the remaining share (11%) is assumed to be natural grassland. We used the thicket, fynbos, and natural grassland shares for the natural restoration land use scenario (8th post-removal scenario). Thus, the natural restoration land use scenario combines the most relevant vegetation classes present in the region. In reality, land restoration will be limited by the local social and biophysical characteristics.

2.1.5. *Supply chain scenarios*

Fig. 2 shows the different assessment steps and supply chain stages. In SA, the eradication of IAPs involves the harvesting of trees mainly with (chain) saws and chemical treatments; followed in the course of the next five years by several treatments (1–3 years’ intervals depending on plant species) to remove (potential) new growth [37]. In this study, it is assumed that trees are harvested manually with chain saws. After clearing, biomass is collected and loaded manually into trailers and transported with tractors to the roadside. At the roadside, biomass is debarked/chipped, loaded into trucks and transported to the pellet plant in Port Elizabeth. In the pellet plant, biomass is pelletized. For biomass pelletization, additional biomass is required for the drying process. For the final stage of the supply chain (electricity production), we considered two scenarios (1) transporting the wood pellets to a local power plant for electricity production in SA (Electricity in SA scenario) or (2) exporting the wood pellets to the Netherlands and generating electricity at a facility in the port of Rotterdam (Electricity in NL scenario).

2.2. *GHG emission calculation method*

Supply chain GHG emissions, including LUC-related GHG emissions, were calculated following a life cycle assessment (LCA) approach using methods in line with the REDII. The REDII methods are applied for consistency reasons given the scope of the assessment (one conversion route involves biomass use in Europe). For the first assessment step (scope 1), in which annualised LUC-related GHG emissions are calculated (Equation (1)), biomass and soil organic carbon (SOC) pools are included [28]. An amortization period of 20 years is assumed for carbon pools to reach equilibrium after IAPs are removed. Therefore, effects of LUC from IAPs to the different subsequent land use scenarios on the carbon pools are calculated over a 20-year time horizon, in line with IPCC and REDII standards [28,29]. The methods to calculate the biomass and SOC pools of each IAP type and land use scenario are present in section 1 of the supplementary material.

In the second and third steps (scope 2 and 3), GHG emissions are calculated for every step of the supply chain (Equation (2)) [28]. Upstream emissions from the production of fuels and products (e.g., diesel) are considered, but emissions involved in constructing facilities, buildings and vehicles are not included. The use stage is also considered. However, wood pellets used for electricity generation are considered carbon-neutral, and CO_2 emissions released during this stage are considered zero [28]. Different GHG emission reporting units are considered in line with each assessment step. For the first step, LUC-related GHG emissions are reported in Mg CO_2 ha^{-1} year^{-1}. For the second step (pellet production), the results are shown in g CO_2eq kg^{-1}; and for the final step, electricity production, results are presented in g CO_2eq MJ^{-1}. The productivity of IAPs input for electricity output (MJ ha^{-1}) is considered in the final assessment step to include the

LUC-related GHG emissions in the overall supply chain emissions. The inventory data and main assumptions for the assessment of the GHG emissions of electricity production of IAPs are presented in section 4 of the supplementary material.

$$e_l = (CS_r - CS_A) * \frac{44}{12} * \frac{1}{20} \qquad \text{Equation 1}$$

Where:

e_l = Annualised emissions from carbon stock changes caused by land use change, Mg $CO_2eq\ ha^{-1}\ year^{-1}$
CS_r = Carbon stock (C) in land associated with the IAPs, $Mg\ ha^{-1}$
CS_A = Potential carbon stock (C) in the successive land use scenarios, $Mg\ ha^{-1}$
44/12 = Conversion factor to convert C to CO_2
1 *year/20 year* = Factor to annualize emissions

$$E = e_{ec} + e_l + e_p + e_{td} + e_u \qquad \text{Equation 2}$$

Where:

E = Total emissions from the use of electricity, $g\ CO_2eq\ MJ^{-1}$
e_{ec} = Emissions from the extraction or cultivation of raw materials, $g\ CO_2eq\ MJ^{-1}$.
e_l = Annualised emissions from carbon stock changes caused by land use change, $g\ CO_2eq\ MJ^{-1}$.
e_p = Emissions from processing, $g\ CO_2eq\ MJ^{-1}$.
e_{td} = Emissions from transport and distribution, $g\ CO_2eq\ MJ^{-1}$.
e_u = Emissions from the fuel in use, $g\ CO_2eq\ MJ^{-1}$

2.3. Water shortage

IAP's high evapotranspiration rates can lead to significant changes in a region's water balance, reduced stream flows and groundwater levels, and can potentially lead to local water depletion [38]. Within IAPs, acacia, eucalyptus and pine are responsible for the most significant impact on the country's water resources [22,23,39,40]. The effect of IAPs on the local water balance was assessed with Equation (3) [41]. Despite that this equation lacks a direct indicator to determine the potential water depletion in the entire region, it provides an adequate estimate of the amount of water that different vegetation types require and use. The spatially explicit daily water shortage was assessed by comparing the evapotranspiration rates from IAPs during the growing season's length with the effective precipitation over the same period. The water shortage was also assessed for each land use scenario. Then, the water shortage from IAPs was compared to the water shortage of the different land use scenarios to determine the net reduction in water shortage. The water shortage was assessed individually for acacia, eucalyptus and pine. However, the results are presented while considering a weighted average in line with IAPs distribution shares (see section 2.1.3). A similar process was done for the natural state land use scenario with thicket, fynbos and natural grasslands assessed individually but results are presented for the corresponding shares. The growth cycle of each vegetation is considered over one year and each corresponding crop/vegetation coefficient (Kc) is applied based on the development stage (see Table SM3 in the supplementary material). This is done to obtain land use and location-specific evapotranspiration rates. The methods to assess evapotranspiration and effective precipitation are presented in section 2 of the supplementary material. Water shortage is expressed in mm year^{-1}.

$$WS_i = \sum_{GC} ET_0 * Kc_{i,j} - \sum_{GC} EP \qquad \text{Equation 3}$$

Where:

WS = Water shortage, $mm\ year^{-1}$
GC= Grow cycle
i= Vegetation type
j = Crop/vegetation growing stage
ET_0 = Reference evapotranspiration, $mm\ day^{-1}$
Kc = Crop/vegetation coefficient
EP = Effective precipitation, $mm\ day^{-1}$

2.4. Socio-economic impacts

The socio-economic impacts are assessed under two performance indicators; supply chain costs and full-time jobs created. The supply chain costs are investigated up to conversion-facility-gate. Therefore, the cost analysis is limited to delivering the biomass in the power plant in SA or in the port of Rotterdam, and biomass conversion costs are excluded. Different sector-based wages are considered in line with regional characteristics. The costs and employment generation related to land rehabilitation after IAP's are removed are discussed but not quantified in the main results. Supply chain costs are presented on a dry basis, ZAR Mg^{-1} and per unit of energy ZAR GJ^{-1}. Full-time jobs are assessed based on a 40-h workweek and presented on an annual basis. One full-time job equivalent (FTE) represents 2080 working hours. FTE's are presented up to the conversion-facility-gate. The total annual biomass output delivered at the conversion-facility-gate is considered to estimate the total amount of jobs created in one year. Direct jobs generated at the conversion facility are excluded. The parameters assumed in the GHG calculations presented in the inventory section, such as dry matter losses and biomass Moisture Content (MC), are applied consistently in the socio-economic analysis. The main regional cost parameters are summarized in Table 1. The specific parameters related to costs and job creation of each step in the supply chain are presented in section 3 of the supplementary material.

3. Results

The results are divided into two main parts. Section 3.1 presents the GHG and water impacts of land use transitions when IAPs are cleared and the land is rehabilitated to the selected land use scenarios. Section 3.2 presents the impacts of mobilizing and delivering IAP biomass at power plants on GHG emissions, costs and employment.

3.1. Environmental impacts of IAP removal and land rehabilitation

3.1.1. LUC-related GHG emissions

On average, the removal of IAPs results in a carbon loss of

Table 1
Main cost parameters according to regional characteristics.

Parameter	Unit	Value
Exchange rate	ZAR: €	18.77[a]
Hourly labor costs agriculture/forestry	ZAR h^{-1}	18.68[b]
Hourly labor costs transport	ZAR h^{-1}	99[c]
Hourly labor costs manufacturing	ZAR h^{-1}	115[d]
Electricity price industry	ZAR MJ^{-1}	7.74[e]
Diesel price	ZAR Mg^{-1}	14,470[f]
HFO price	ZAR Mg^{-1}	304[g]
Annual interest rate	%	7

[a] Exchange rate average for 2020 between ZAR and € [42].
[b] According to the new National Minimum Wage (NMW) rate for farm/forestry workers [43]. In SA agricultural and forestry sector, minimum wages are common practice [44].
[c] Average heavy truck driver salary in SA [45].
[d] [46].
[e] Electricity price for large business electricity consumers (6600V and above). Price includes average between winter and summer rate. Basic and maximum demand charges are also included [47].
[f] Average price of 2020 [48].
[g] [49].

approximately 11.9 Mg CO_2 $ha^{-1}year^{-1}$ (Fig. 3). The carbon loss mainly results from carbon losses stored in the above ground biomass and only to a limited extent from changes in the SOC pool. For all successive land uses, a carbon uptake is projected after IAPs are cleared. However, the net carbon flux is positive for almost all successive land use scenarios, i.e. net CO_2 emissions. IAPs thrive under local biophysical conditions and produce more biomass (carbon) than other vegetation types. IAPs are fast-growing tree species and can develop large amounts of above ground biomass in short periods compared to the other land uses and therefore store more carbon in the biomass carbon pool.

The highest LUC-related net carbon emissions are projected for annual cropland and pastures. The establishment of these land uses after the land is cleared from IAPs results in annual emissions of 7.6 Mg CO_2 $ha^{-1}year^{-1}$ for cropland and 7.3 Mg CO_2 $ha^{-1}year^{-1}$ for pastures. Annual cropland is characterized by low carbon storage, given its annual harvest cycles. Most of the carbon stored in biomass during the growing cycle is lost when the crops are harvested, resulting in an almost balanced net carbon flux for biomass carbon. When natural grasslands are reestablished, 6.9 Mg CO_2 $ha^{-1}year^{-1}$ is potentially emitted. The dry semi-arid conditions and relatively shallow root systems result in little biomass development for grasslands. Therefore, the high carbon loss is mainly related to the difference in biomass between IAPs and natural grasslands. Net carbon emissions also occur when IAPs are replaced with fynbos (2.9 Mg CO_2 $ha^{-1}year^{-1}$). However, this carbon loss is small compared to the other land use transitions. The SOC pool changes are almost insignificant given that for a 20-year horizon, the carbon loss from LUC is restored almost entirely. Only two scenarios result in a negative carbon flux (CO_2 accumulation). Carbon is accumulated when IAPs are replaced by dense forests (−2.9 Mg CO_2 $ha^{-1}year^{-1}$) or low forest and thicket (−1.4 Mg CO_2 $ha^{-1}year^{-1}$). Both of these land uses can develop more biomass under local biophysical conditions than IAP's and thus, accumulate more carbon in the biomass carbon pool. However, these land uses represent natural ecosystems where little to no degradation/deterioration has occurred. Still, the carbon accumulation in these scenarios is low given that these vegetation types are adapted to the local conditions and haves biomass yields similar to IAPs. The net carbon flux is positive when the land is restored to its natural state. Nevertheless, the net carbon emissions are relatively small 0.9 Mg CO_2 $ha^{-1}year^{-1}$. Most of the region is within the thicket biome. The land use transition between both uses generally results in a net carbon accumulation.

3.1.2. *Water shortage*

Fig. 4 shows the average water balance of IAPs and the corresponding water balances of the different land use scenarios. On average, IAPs show the highest water shortage. The considerably high evapotranspiration rates combined with low annual precipitation result in a water deficit of 1,222 mm $year^{-1}$ for IAPs. This signifies that, on average, an additional 12,221 m^3 ha^{-1} is potentially withdrawn from different water sources (besides precipitation) by IAPs for their growing cycle. To illustrate, IAPs are characterized by a deep root system that allows them to access deeply stored groundwater. The use of these water sources can disturb water tables and potentially results in local water depletion. The water balance for all other land uses, except for annual cropland, is positive. Precipitation is sufficient for annual cropland (barley) to meet the crop water requirements. Thus there is no need for other water sources (e.g., irrigation). Conversely, for other land uses, the water supply from precipitation is insufficient for their vegetation development and other water sources are potentially utilized.

The difference in water demand between IAPs and other potential land uses varies between −1,263 and −12 mm $year^{-1}$. On average, the removal of IAPs results in water savings when considering any potential land use transition. The highest water savings are projected for annual croplands, followed by pastures. The growth cycle of annual croplands (barley) is considerably shorter (5–6 months) than the growth cycle of IAPs (12 months) or any other potential land use. The lowest water savings are achieved when IAPs are replaced with dense forest (12 mm $year^{-1}$). The high evapotranspiration rates of dense forests result in a water deficit similar to IAPs. However, different from IAPs, dense forest areas are generally limited to mostly riparian areas. Water savings are also projected when the land is replaced with low forest and thicket (244 mm $year^{-1}$) or fynbos (472 mm $year^{-1}$). Both land uses are well adapted to local biophysical conditions and report lower evapotranspiration rates and less water use than IAPs. The potential land use transition from IAPs to orchards (citrus) results in 427 mm $year^{-1}$ water savings. Although the evapotranspiration rates of orchards are high for several months, orchards result in less water deficit than IAPs, as the high evapotranspiration rates coincide with the rainy season. A water savings potential of 361 mm $year^{-1}$ (3,610 m^3 ha^{-1}) is projected if the IAPs area is restored to its natural state.

3.2. *Impacts of using IAPs for bioenergy*

3.2.1. *GHG emissions of pellet production*

As shown in Fig. 5, the sum of GHG emissions from IAP biomass supply up to the pellet plant gate is 150 g CO_2eq kg^{-1}. The pelletization step is the process with the most significant impact along the entire supply chain (67 g CO_2eq kg^{-1}). Two factors mainly cause this: first, the electricity demand of the pellet mill (e.g., grinding, densification) and the associated upstream emission of fossil-dominated electricity supply in SA, and second, the additional wood fuel demand for drying. Approximately 0.5 kg of wood is required to reduce the moisture content

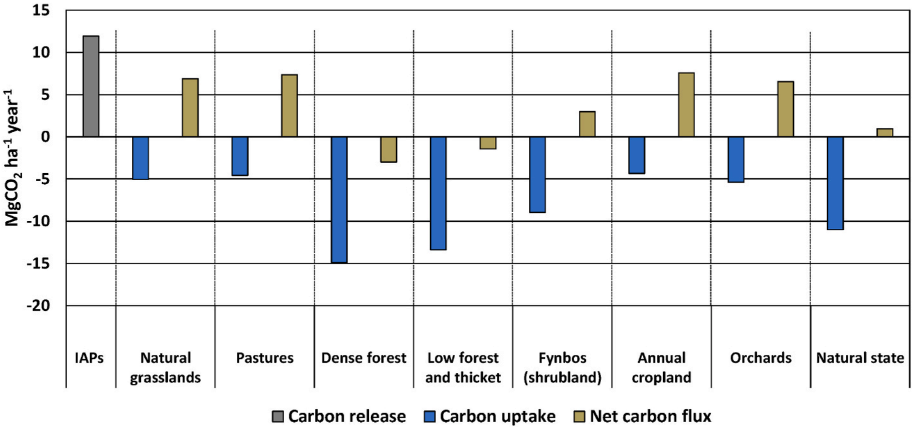

Fig. 3. Carbon loss of IAPs removal, carbon uptake from land use scenarios and net carbon flux (carbon release IAP – carbon uptake) in Mg CO_2 $ha^{-1}year^{-1}$ (20 year amortization period).

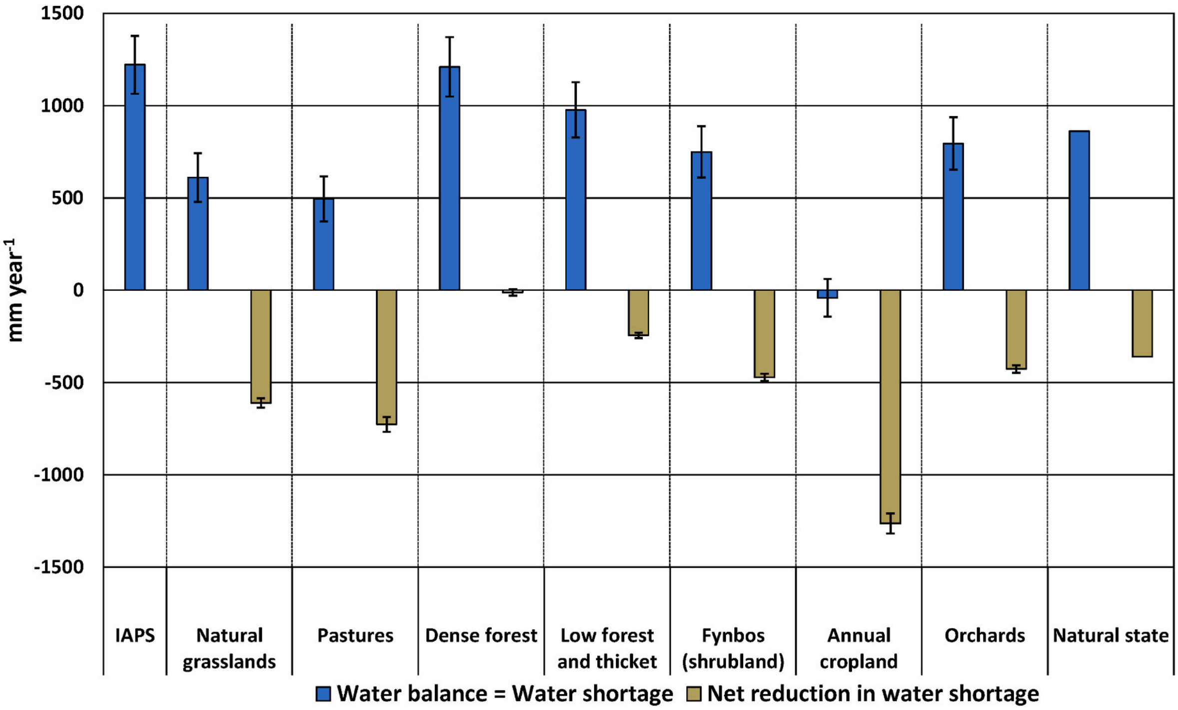

Fig. 4. Water shortage (evapotranspiration - effective precipitation) of IAPs compared to other land use scenarios (in mm year^{-1}). The ranges indicate two standard deviations of the spatial variability of the water balance due to the heterogeneity in the biophysical conditions.

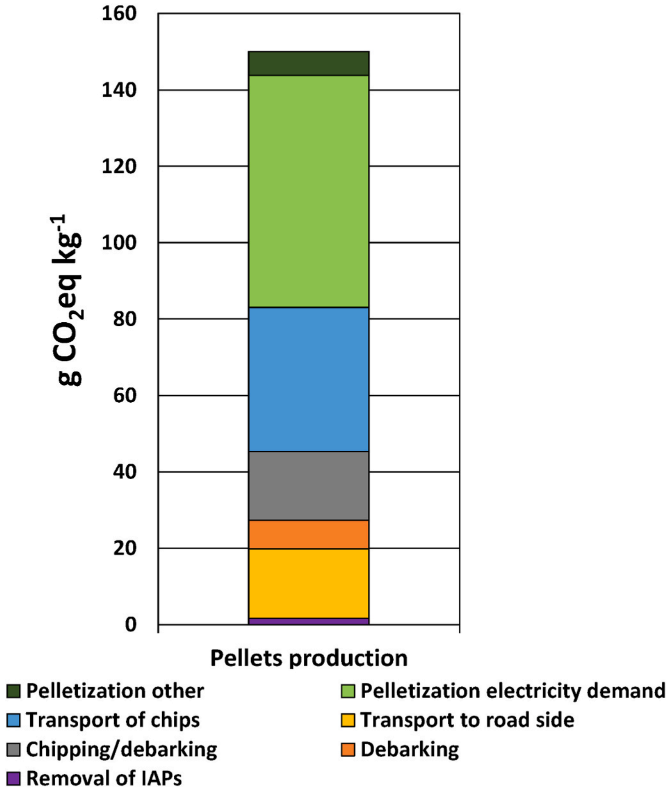

Fig. 5. GHG emission from IAPs used for pellet production in Port Elizabeth.

from 50% to 10% in the drying process for each kg of pellets output. This additional wood supply results in an increase in GHG emissions for the upstream processes of pelletization. The impact of transport on GHG emissions is lower than the pelletization process. The biomass required to meet the pellet plant's annual biomass demand can be sourced relatively close to the pellet plant location. Within an 82 km service area, there is enough biomass to supply the pellet plant requirements, including the additional wood required for drying. Mobilizing IAP biomass from clearing site to road has an impact of 18 g CO_2eq kg^{-1}. This impact is lower than other processes but is relatively high considering that biomass is only transported for 8 km on average. The impact of wood chipping is similar to the transport to the roadside stage given the intensive use of diesel to kg wood chipped ratio. This ratio is almost half for the debarking process, resulting in nearly half of the emissions of the chipping step. The GHG emissions from the IAPs harvesting/removal are comparatively low and contribute marginally to the overall supply chain emissions.

3.2.2. GHG emissions for electricity from IAP pellets

The aggregate supply chain GHG emissions of electricity from IAP pellets (excluding LUC-related GHG emissions) are 31.5 g CO_2eq MJ^{-1} for electricity generation in SA and 31.2 g CO_2eq MJ^{-1} for electricity generation in NL (Fig. 6-A). The main difference between the two options is in transportation, i.e., distance and mode of transport. However, the impact of transport-related emissions between the two options is minimal. In SA, pellets are transported by truck over a long distance (1,000 km) to the closest power plant. When pellets are exported, bulk carriers deliver the pellets from the pellet plant location in Port Elizabeth to Rotterdam. Despite the long maritime distance between ports, bulk carrier's transport efficiency is considerably higher compared to transport by truck over long distances.

The impact of LUC-related GHG emissions (3.9 g CO_2eq MJ^{-1}) is relatively low compared to the emissions in the supply chain itself (Fig. 6-B). The net carbon fluxes that result from the carbon release from the eradication of IAPs followed by the carbon uptake of rehabilitating the land to its natural state is relatively small (see section 4.1.1). However, when the land use is replaced with annual cropland, total supply chain GHG emissions can increase by 32 g CO_2eq MJ^{-1}. It could, however, also decrease by 12 g CO_2eq MJ^{-1} when IAPs are replaced by dense forests. Both supply chains, including LUC-related GHG emissions, can comply with REDII 70% GHG savings requirement for 2021 and 80%

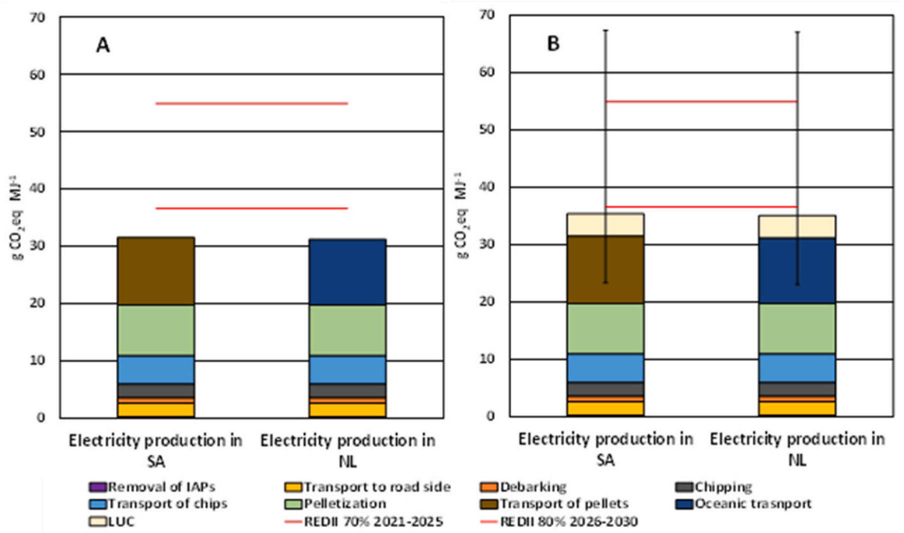

Fig. 6. GHG emission from IAP pellets used for electricity generation in South Africa or the Netherlands (in g CO_2eq MJ^{-1}). Figure A excludes the carbon stock changes induced by IAP removal and land rehabilitation to its natural state. Figure B includes the carbon stock changes induced by IAP removal and land rehabilitation to its natural state. The ranges indicate the carbon stock changes from other land use transitions.

GHG savings requirement after 2025. However, complying with REDII requirements is only feasible when the land is restored entirely to its natural state(i.e. thicket or dense forest). Conversely, if the land is dedicated to natural grasslands, pastures, fynbos, orchards, or annual croplands, the supply chains would fail to comply with the REDII GHG emissions savings targets.

3.2.3. Supply chain costs of using IAPs for bioenergy

The supply chain cost of pellets is 5,344 ZAR Mg^{-1} (284.7 € Mg^{-1}) delivered at the power plant in SA and 2,535 ZAR Mg^{-1} (159.1 € Mg^{-1}) delivered at Rotterdam port as shown in Fig. 7-A. Results are also shown on an energy basis (Fig. 7-B). The cost of pellets in SA is considerably higher due to the long distance between Port Elizabeth to the closest power facility (1,000 km) and the lack of railway infrastructure to enable efficient transport. The transport of pellets accounts for approximately 52% of the total supply chain costs in SA. The largest share of the pellets transport cost corresponds to the truck kilometer rate. Conversely, the cost of delivering pellets to NL is significantly lower. Despite that port and voyage costs can be perceived as high, the overall costs when considering the ship cargo capacity are low. The cost of pelletization corresponds to 1,200.4 ZAR Mg^{-1} (64 € Mg^{-1}). The biggest share of pelletization costs is the operating costs (80%), mainly the additional biomass costs required for drying (56%). Drying with biomass requires that additional feedstock is mobilized from the harvesting location to the pellet plant. This drying biomass demand generates a cost increase in all logistics up to pelletization. Removing IAPs corresponds to 10% of the SA supply chain's total costs and 19% for the NL supply chain, 561 ZAR Mg^{-1} (29.9 € Mg^{-1}) for both scenarios. The removal costs are higher than for chipping (49.5 ZAR Mg^{-1} – 2.6 € Mg^{-1}) and transport to roadside (295.6 ZAR Mg^{-1} – 15.7 € Mg^{-1}), due to the high number of workers involved in IAP removal. The transport of chips from the roadside to the pellet plant is estimated at 427.4 ZAR Mg^{-1} (22.7 € Mg^{-1}).

3.2.4. Supply chain employment of using IAPs for bioenergy

The total annual direct full-time jobs generated from sourcing IAPs up to the conversion-factory-gate is 604 for SA and 525 for the NL (see Fig. 8). This indicates that running operations over a year for both supply chains would generate direct employment full-time for 604 people if electricity is generated in SA and 525 if electricity is produced in the NL. For both supply chains, most of the jobs are created in SA. However, when pellets are shipped to the NL, it is uncertain under which

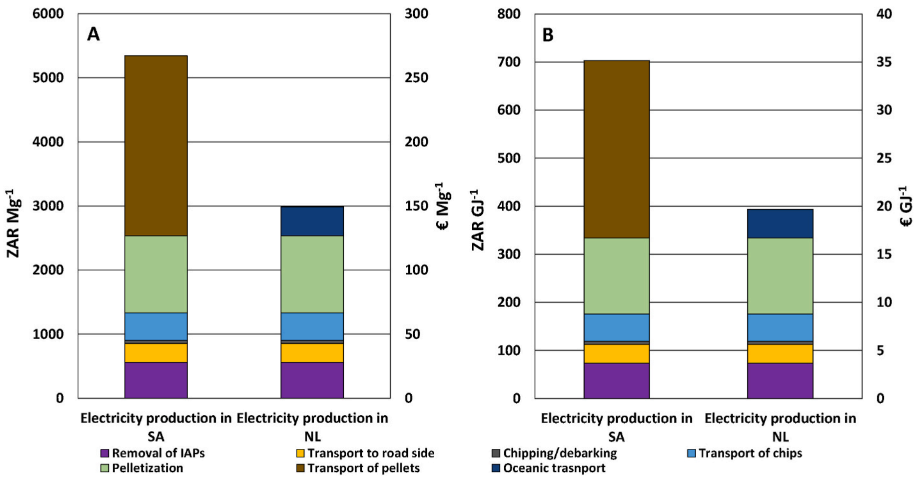

Fig. 7. Supply chain costs of IAP pellets used for electricity generation in South Africa or the Netherland, delivered at conversion-factory-gate. Results are expressed on a mass and energy basis.

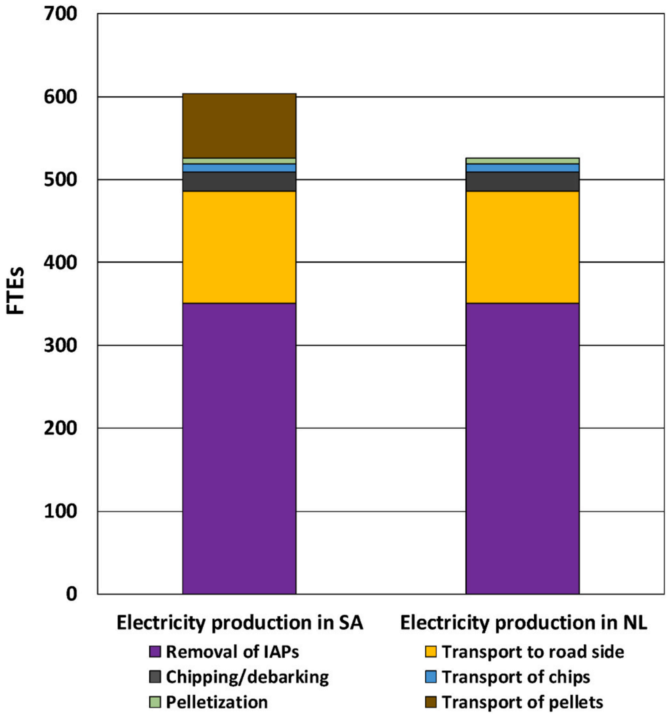

Fig. 8. Supply chain employment from IAPs pellets used for electricity generation in South Africa or the Netherlands, delivered at conversion-factory-gate.

country ship members are employed. Therefore, crew jobs are not considered. The most significant number of jobs are created in the stages that require more manual labor, such as IAP removal and transport to the roadside. Removing IAPs to meet annual biomass pellet demand requires approximately employing 351 people on a full-time basis. Most of these positions are related to chain saw operations for tree cutting/removal. Transporting biomass to the roadside also requires several workers. About 135 full-time jobs are required for this stage; most of these jobs are related to manually loading the biomass in the tractor transport trailers. It takes approximately 1 h to collect and load manually 1 m^3 of IAPs biomass. The transport of chips from the roadside to the pellets plant requires a small number of full-time employees (10), while the transport of pellets to the power plant requires a more significant number (78). The large difference in employment of both stages is caused by the difference in distances and consequently working time. To illustrate, it takes 1.5 h to transport biomass from the roadside to the pellet plant, while it takes 18.2 h to.travel from the pellet plant to the power plant. Few jobs are generated at the pellet plant. Approximately 7 workers are required to run operations annually due to the more mechanized systems operations than in other supply chain stages.

4. Discussion

4.1. GHG emissions from landscape restoration and using IAPs for bioenergy

IAPs are a significant carbon sink, and removing these will result in a net loss of carbon (depending on land use transition). The carbon fluxes resulting from LUC from IAPs to the natural state will rely mainly on the type of vegetation that is actually restored and to what degree it can be regenerated to the original condition. For example, the carbon stock (biomass + SOC) of intact Baviaans Spekboom Thicket land is estimated at 61.13 Mg ha^{-1} [50]. If IAPs are restored to Baviaans Spekboom Thicket land instead of Fish Spekboom Thicket land (assumed in this study, 73 Mg ha-1, see section 1 in the supplementary material), the net carbon flux would be positive, resulting in an overall carbon release. Furthermore, the carbon release can be considerably higher if an intact (without degradation) natural state is not reached. Net carbon fluxes will also depend on the vegetation status of IAPs prior to conversion and designated land use (vegetation) after restoration, and both can vary considerably. To illustrate, in this study, IAP's average yields are set at 65 Mg ha^{-1}. However, in similar biophysical conditions, other studies have reported yields of approximately 66–68 Mg ha^{-1} for eucalyptus and 78 Mg ha^{-1} for Acacia plantations [29,51]. In addition, it is still uncertain whether, after the removal of IAPs, the soil and biomass will reach the expected state of carbon equilibrium [19]. If such carbon equilibrium states are not reached, potentially more carbon will be released [29]. Dedicating the treated land to annual crops or pastures for cattle can result in higher GHG emissions from agricultural-related activities such as fertilizer application or methane-derived enteric fermentation [52]. Other studies have reported similar net carbon losses varying between 20 and 70 Mg ha^{-1} (depending on land use transition) [19,53,54].

Significant GHG savings are possible by restoring lands with natural vegetation, mainly thicket/fynbos for the Port Elizabeth region. However, if other land uses such as annual croplands and pastures are implemented after IAPs are cleared, the LUC-related GHG emissions from such transitions can offset the benefits achieved of using biomass for electricity production [7,9,19]. The question is if these LUC-related emissions should be allocated to bioenergy. The calculation rules of REDII require to account for LUC-related GHG emissions unless the biomass is categorized as a residue. According to REDII article 2, residues are defined as "… *substance that is not the end product(s) that a production process directly seeks to produce; it is not a primary aim of the production process and the process has not been deliberately modified to produce it*" [28]. Independent of the final biomass use, IAPs are removed with the primary objective of restoring the land and enhancing water and biodiversity protection services [37]. Therefore, after the land is treated, the use of IAPs does not intervene with the primary objective of land restoration. Currently, IAPs are not grown and removed for the purpose of bioenergy, or other end uses. Since their introduction, IAPs have spread across the country over time, as they are highly adapted to SAs biophysical conditions [55]. Therefore, utilizing IAPs as a feedstock for any purpose is not the primary aim of the land restoration process and does not seek to produce additional IAPs. The use of IAPs could be considered carbon neutral upstream of collection if they are considered a residue in line with REDII. However, regardless of the feedstock classification and associated calculation rules, removing IAPs will result in net carbon losses in almost all cases.

Currently, biomass is left on site unused or used on a small scale by the local communities as fuelwood [9]. Nevertheless, using IAPs for electricity can result in indirect effects as it could displace current IAPs feedstock uses (fuelwood) or generate additional pressure to produce IAPs for economic purposes. However, producing IAP feedstock types requires multiple permits and is not permitted in treated areas [15]. The applied model is unsuitable for assessing the possible consequences of replacing different end uses as it is static and independent of an economic context [56]. Other types of frameworks (i.e., consequential LCA) can be applied to account for such effects.

IAPs as feedstock for electricity production in SA can help to reduce SA GHG emissions and to decarbonize the energy sector. Approximately 226 g CO_2eq MJ^{-1} are saved when pellets derived from IAPs feedstock are used for electricity production and replace conventional electricity production in SA. Similar results were found in other studies with GHG emission savings ranging between 70 and 250 g CO_2eq MJ^{-1} [7,9]. However, in these studies, LUC-related GHG emissions were not accounted for, and biomass is not pelletized before co-firing at the power plant. Dedicating the whole pellet production to electricity generation in SA and restoring the land to its natural state can lead to GHG emission savings of 206,112 Mg CO_2eq $year^{-1}$. In SA, 48% of annual GHG emissions are from electricity and heat production [57]. Therefore, dedicating the whole pellet production can reduce on a cumulative basis

1.7%. GHG emissions from electricity and heat production. In addition, it can provide electricity to 67,000 people annually since the annual average per capita electricity consumption in SA is 3,759 kWh [58].

The GHG savings from electricity production in NL with IAPs derived pellets from SA are considerably lower. The electricity mix in NL has a lower share of fossil-based sources and thus, GHG emissions from conventional electricity production are lower. About 112 g CO_2eq MJ^{-1} GHG savings are accounted for in the NL supply chain, equivalent to 102,144 Mg CO_2eq $year^{-1}$. However, there could be limitations to introducing IAPs pellets in the European market as the wood properties from these tree species might not meet European standards for industrial pellets. For example, for large installations, the ash content of the feedstock should be lower than or equal to 2% [59]. This threshold can potentially not be met according to the properties of some species included in our study. A study of wood properties in the Western Cape reported a 2.1% ash content for acacia and 2.3% ash content for eucalyptus [60]. Additional research is required to assess the wood properties from the IAPs in the study area to estimate better the potential to export IAPs pellets to the European market.

The selected supply chain configuration for electricity production in SA poses several limitations. All coal power plants in SA are located inland and remote from seaports. The closest power plant is located 1,000 km away from Port Elizabeth and the mobilization of biomass by road transport can be costly and inefficient [61]. It is suggested that transport costs are one of the main barriers to biomass exploitation [6]. In addition, pelletization is not required for co-firing biomass at the power plant. Wood chips could potentially be transported directly from the supply area to the power plant. Still, the IAPs supply location is far from the nearest power plant location. The benefits of biomass pelletization are valuable for long-distance intermodal biomass supply chains in which there are clear GHG emissions and cost benefits of condensed bulk transport [61,62]. Thus, from a logistic perceptive, the export of pellets seems more suitable for a supply chain configuration with a pellet plant located in Port Elizabeth. However, the export of pellets for electricity production in other countries such as in the NL, as assessed in the study, would considerably diminish the GHG emissions savings in SA. Nevertheless, coal power plants in SA are located near coal mines, and many will be decommissioned in the coming decade. New plants could also be developed near port regions, such as Port Elizabeth, to provide carbon benefits for biomass supply chains. Other final uses of pellets should also be explored. Final uses such as pellets for the residential market could offer higher benefits for this supply chain and SA GHG emission mitigation targets. In addition, other supply chain configurations could be assessed, such as drying the wood at the harvesting site could reduce MC content and GHG emissions from logistics.

4.2. Water savings

Clearing the land of IAPs will result in water savings independently of the succeeding land use. Water savings are particularly important because only 9% of the country's annual precipitation ends up as water in rivers or aquifers [75]. It can also reduce the pressure on irrigation systems and overall water consumption in the country. To illustrate, on average 7,659 m^3 ha^{-1} are used for irrigation purposes in SA [63]. This signifies that if the land is restored to its natural state, 47% of water demand for irrigation (ha basis) could be covered by allocating the additional water previously utilized by IAPs compared to the natural landscape. Despite that irrigation supports only 25–30% of SA agricultural production, 90% of the country's high-value crops such as potatoes and fruits are irrigated [63]. High water savings are reported when IAPs are replaced with annual crops (Barley), pastures and orchards. However, the overall savings can be lower when considering other water uses such as water for livestock production [64], irrigation for orchards and using the land for other purposes after harvesting annual crops.

The water savings are estimated based on the difference between the annual water deficit in IAPs and the successive land use scenarios after IAP removal. Therefore, it describes particularly whether IAPs use more or less water than the potential land use scenarios according to local specific biophysical characteristics. Also, despite that the water balance includes important parameters such as temperature and precipitation, it neglects others such as soil characteristics. Crop/vegetation coefficient values were not available for the thicket vegetation type. Crop/vegetation coefficient values for thicket were assumed as an average between dense forest and fynbos, as thicket is considered to be a transition ecosystem between shrubs and forest [65]. Thicket-specific coefficient values could lead to different water savings results. However, it is widely reported that IAPs generally use more water than thicket vegetation [22,32,66,67]. Climate data for 2020, instead of long-term averages, was used in line with the study's temporal scope to represent current conditions. This data set is already corrected to account for extreme events such as prolonged dry spells. Thus, it is expected that using long-term averages would not considerably affect the results. The results are likely to be affected when climate change is considered, given that drought episodes are projected to occur more frequently in the future [13].

4.3. Supply chains costs of using IAPs for bioenergy

The supply chain costs are considerably higher for electricity production in SA than for the export of IAPs pellets to NL. The high logistics cost of delivering pellets from Port Elizbeth to the closest power plant makes it infeasible to compete with electricity market prices without subsidies. Average market electricity prices stand at 0.44 ZAR MJ^{-1} [6]; this is approximately 63% less than the costs estimated in this study for the SA supply chain (0.7 ZAR MJ^{-1}). Furthermore, conversion costs are not included. Thus, from a market perspective, electricity production from IAPs sourced in the Port Elizabeth region is expensive. However, the cost assessment disregards the overall hidden benefits from using IAPs and rehabilitating ecosystem services. From a cost-savings perspective, the overall benefits from removing IAPs and carbon emissions reduction from displacing fossil fuels could sum up to 69,682,555 ZAR $year^{-1}$ for water services and 24,076,800 ZAR $year^{-1}$ for carbon services when allocating the whole pellet output to electricity production in SA. These savings are obtained based on a water value of 1.5 ZAR $m^{3\ -1}$ and a carbon tax of 1 ZAR Mg^{-1}(CO_2eq) [6,68]. These cost savings externalities translate into 0.11 ZAR MJ^{-1} that could be allocated to reduce the overall electricity price from IAPs. However, the overall cost savings could decrease if the land use after IAP removal is considered. In addition, replacing IAPs with land uses that provide an economic activity for the region, such as citrus orchards, can result in additional cost benefits.

In recent years, pellet imports to the Netherlands were widely sourced from the United States (US) and Canada [69]. The market price of pellets delivered at Rotterdam can vary between spot prices and contract prices. Between 2012 and 2018, CIF ARA spot prices from the US and Canada (delivered at Rotterdam) varied between 107 € Mg^{-1} to 137 € € Mg^{-1} and contract prices varied between 131 € Mg^{-1} and 182 € Mg^{-1} [70]. Compared to CIF ARA spot prices of wood pellets, the calculated costs of SA wood pellets (159.1 € Mg^{-1}) are high. However, note that most of the pellet imports from these countries to the Netherlands are traded under long-term price contracts [71]. Therefore, comparing the costs to contract prices could offer a more realistic benchmark. Hence, these pellets could potentially compete with other international pellet markets. However, it highly depends on external factors such as exchange rates, shipping rates, and market conditions. The estimated costs also appear to align with the costs of pellets found in literature ranging between 88 € Mg^{-1} to 279 € Mg^{-1} [71].

The cost estimates are based on a desk study and are subject to high uncertainty. For example, average 2020 time charter rates (8,150 USD day^{-1}) were applied to estimate maritime shipping costs. However, in the last two years, supramax charter rates have surpassed the 14,000 USD day^{-1} barrier for several months [72]. A substantial increase in time charter rates would lead to an additional 4 € Mg^{-1}. The export of pellets is submitted to market conditions that are considerably affected by the exchange rate between Euros and South African rand. The whole supply chain operates on a South African rand basis except for ocean freight. Profits of wood pellets exports to NL are made on a Euro basis. An adverse and volatile exchange rate (e.g., depreciation of the ZAR) can considerably affect the cost margins along the whole supply chain and result in an unsustainable pellets-export business. Preliminary costs of rehabilitating the land are estimated between 6,100 ZAR ha^{-1} to 12,200 ZAR ha^{-1} (corrected for inflation) for fynbos and thicket [73,74]., Including these costs would increase the overall supply chains costs by approximately 0.027 ZAR MJ^{-1} to 0.55 ZAR MJ^{-1}. These costs could be addressed through a public-private partnership with clear incentives for both sides, given that in some cases, the costs of rehabilitating can drastically reduce the cost of follow-up treatments [67]. In addition, ecosystem services and biodiversity conservation can provide additional incentives for land restoration.

4.4. *Supply chain employment of using IAPs for bioenergy*

Job creation is crucial for social development and poverty alleviation, both at the top of the agenda for SA [2].The Working for Water programme generated almost 25,000 full-time jobs on a country level in 2017. However, most of these jobs were seasonal and not stable over more extended periods [15]. Instead, the supply chains investigated in this study potentially could keep workers on a full-time basis over the pellet plant expected productive lifetime (15 years). Biomass potentials are given on an annual basis over a 20-year time horizon of availability. Thus, biomass supply can be carried out in the selected region beyond the pellet plant lifetime. In addition, Working for Water is defined as an Extended Public Works Programme in the Department of Public Works. Therefore, the remuneration for workers is lower than in a private project. For example, the current minimum wage for workers employed on an expanded public works program is 11.42 ZAR h^{-1}; this is almost 8 ZAR h^{-1} less than employees in the agriculture and forestry sectors [43]. Therefore, a pellet plant project in the Port Elizabeth region could generate more and better-paid employment. However, it must be highlighted that Working for Water targets underprivileged communities in order to contribute to poverty alleviation at the national level. Additional jobs could be created if restoring the land is accounted for in the pellet plant project. To meet the input requirements of the pellet plant with a capacity of 120,000 Mg $year^{-1}$ pellets, 2940 ha of IAPs need to be cleared annually. It is suggested that rehabilitating 1 ha under a native thicket ecosystem requires 50 working days [73]. Therefore, restoring the total treated land could lead to an additional 403 workers employed full-time annually.

5. Conclusion

The eradication of IAPs results in trade-offs between GHG emissions, water savings, and socio-economic impacts. The land use transition dictates to a large extent the magnitude and direction (positive or negative) environmental effects resulting from IAPs removal. The eradication of IAPs could reduce water shortages with 120 m^3 ha^{-1} $year^{-1}$ if replaced with dense forests, to up to 12,630 m^3 ha^{-1} $year^{-1}$ if replaced with annual cropland without irrigation. However, replacing IAPs with annual cropland will also result in the highest net carbon losses from LUC (7.3 Mg ha^{-1} $year^{-1}$). Generally, net carbon losses will occur when considering the land use transitions after IAPS removal, even when land is rehabilitated to its natural state (3.3 Mg ha^{-1} $year^{-1}$). However, independent of the land use transition, removing IAPs results in water savings and job creation. These benefits can also amplify other ecosystem services, such as the conservation of biodiversity and socio-economic development. Trade-offs of using IAPs for bioenergy need to be considered for the sustainable development of the biomass sector.

The use of IAPs for electricity generation can generate employment and reduce GHG emissions when fossil electricity is replaced. However, the reported GHG savings depend on whether IAPs are classified as a residue or not. This classification will determine whether LUC-related GHG emissions should be allocated to bioenergy or allocated to the eradication program itself. This study explored both options (with and without allocation) separately to provide insights into the effect on the performance of the supply chain and possible trade-offs between impacts.

If pellets are exported to the NL, both 2021 and 2025 REDII GHG emission reduction criteria can be met. However, if IAPs are not classified as a residue, meeting the REDII criteria will rely mostly on rehabilitating the land to its natural state. There are clear trade-offs between environmental and social benefits with costs. The costs of producing electricity in SA from IAPs sourced in the Port Elizabeth region are high (5,344 ZAR Mg^{-1}, 284.7 € Mg^{-1}), due to high logistical costs. However, it will employ 604 workers on a full-time basis. A public-private partnership is essential to share electricity production costs and unleash the environmental and social benefits from such supply chains. From an economic perspective, exporting the pellets to NL seems a more viable strategy than electricity production in SA. However, the GHG emission savings from using IAP pellets would be accounted for in NL. Therefore, other IAP end-uses in SA can be more adequate to avoid long-distance transport given economic constraints. This study is an important step forward in developing sound land use planning for IAP's removal and use.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biombioe.2022.106340.

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