Biomass and Bioenergy 150 (2021) 106096

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: www.elsevier.com/locate/biombioe

Regionalized cost supply potential of bioenergy crops and residues in Colombia: A hybrid statistical balance and land suitability allocation scenario analysis

Ahmed Younis [a,*], Yeanitza Trujillo [a], René Benders [a], André Faaij [a,b]

[a] Integrated Research on Energy, Environment and Society (IREES), University of Groningen, the Netherlands
[b] TNO Energy Transition, Utrecht, the Netherlands

ARTICLE INFO

Keywords:
National resource assessment
Regionalized biomass potential
Spatial cost supply maps
Hybrid statistical land use analysis
Colombia

ABSTRACT

The Colombian agricultural sector has the capacity and ambition to reduce its land use and GHG emissions through sustainable intensification of livestock production. However, the impact of such pathway on the availability of land for bioenergy crops production has not been thoroughly investigated. Moreover, previous assessments of the role bioenergy in Colombia have mostly focused on residues, in isolation of land use policies.

To address this gap, we propose a hybrid statistical land balancing and suitability allocation approach to estimate long term projections of the cost–supply potential of bioenergy crops and residues. Regionalized to the 32 Colombian departments (administrative divisions), this approach could provide higher resolution than global assessments, while avoiding the complexity of spatially explicit methods. We investigated three scenarios covering the uncertainty of socioeconomic drivers and agricultural and livestock productivity factors.

Our results suggest that pursuing progressive land use policies (SSP1 scenario) could release up to 14 Mha of land by 2050, which could be available to produce perennial bioenergy crops. The cumulative potential of crops in SSP1 could reach up to 2200 PJ, where about half of this potential could be attained at 7 $ GJ^{-1} or less. Potential supply centers could be identified in Orinoquía, Andean, and Caribbean regions for energy crops and the Pacific region for residues. Our findings indicate that there could be an opportunity to create synergy between the low carbon development strategies of the land use and energy sectors in Colombia.

1. Introduction

Bioenergy could play an important cost–efficient role in transitioning towards a low–carbon economy and achieving stringent mitigation targets of greenhouse gases (GHG) [1–4]. The potential development of a bio–based economy critically depends on the availability of biomass feedstock [5], e.g. as demonstrated by Younis et al. for the case of Colombia [6]. However, the global estimates of the biomass supply potential have widely diverged [7–13]. One main cause of this non-heterogeneity is the lack of consensus over the potential for large-scale conversion of land for the production of dedicated energy crops [7,14], and its subsequent impact on food and water security, biodiversity conservation, and loss of carbon stock through land use change [11,15–19].

Globally, the agriculture, forestry, and other land use (AFOLU) sector accounts for just below one quarter of the total anthropogenic GHG emissions [20]. By contrast, its relative contribution is higher in Latin America, e.g. up to 55% of the national emissions in Colombia [21,22]. The main source of AFOLU emissions is the deforestation of tropical forests in Latin America, Southeast Asia, and sub-Saharan Africa [23–25]. The primary driver of deforestation in Colombia, and more generally Latin America, is the land conversion to pasture for extensive cattle ranching [26,27]. The Colombian cattle breeding sector exhibits low productivity [28], with an average national carrying capacity[1] (*CC*) of 0.6 large animal unit equivalent (LAU) per hectare [29]. The emission intensity of cattle production is highest in Latin America, South Asia, and sub-Saharan Africa, where such low productive systems prevail [30].

Regarding the biomass resources, global assessments have identified

* Corresponding author. Nijenborgh 6, 9747 AG, Groningen, the Netherlands.
E-mail address: a.i.m.younis@rug.nl (A. Younis).

[1] The carrying capacity (*CC*) indicates the number of grazing LAU that a unit area of land can support on the long-term, i.e. while maintaining or improving forage and other vegetation and related resources [149]. One LAU represents an adult cow of 450 kg.

https://doi.org/10.1016/j.biombioe.2021.106096
Received 6 October 2020; Received in revised form 17 February 2021; Accepted 22 April 2021
Available online 13 May 2021
0961-9534/

Abbreviations

1G	First generation
A_{+VE}	Area of positive imbalance (abundance)
A_{-VE}	Area of negative imbalance (shortage)
A_{3F}	Area for food, feed, & fiber production
A_{3F*}	A_{3F} after redistribution of imbalances
A_{AGF}	Area within the agricultural frontier
A_{BAL}	Area for land balancing check
A_{BIO}	Area available for biomass production
A_{CRP}	Area of cropland
A_{DST}	Area for balancing redistribution of land
A_{EXC}	Area of legally excluded zones
A_{FRY}	Area of commercial forestry plantations
A_{NFR}	Area of natural forests
A_{PST}	Area of grazing pastureland
A_{SRP}	Area of surplus land
A_{SUT}	Area of suitable land for biomass
A_{TOT}	Total departmental surface area
AEZ	Agroecological zoning
AFOLU	Agriculture, forestry, and other land use
$C_{Capital}$	Annualized capital cost of biomass crop production
C_{CRP}	Total annualized cost of biomass crop production
C_{Ferti}	Annual fertilizer cost of biomass crop production
GHG	Greenhouse gases
GS	Marginally suitable land
ha	hectare
HDI	Human Development Index
HI	Harvesting index
iSPS	Intensive silvopastoral system
LAU	Large animal unit
LHV	Lower heating value
LOSS	Supply chain losses
LW	Final live animal weight
M	Moisture content
MADR	The Colombian ministry of agriculture
MS	Moderately suitable land
NAMA	Nationally appropriate mitigation actions
NS	Not suitable land
P_{Ferti}	Fertilizer price
P_{Land}	Land rental price
POP	Population
$PROD_{CROP}$	Annual crop production
$PROD_{FEED}$	Annual production of feed crop
$PROD_{FOOD}$	Annual production of food item
$PROD_{MONO}$	Annual production of monogastric animal product (meat)
PROFOR	Commercial potential of reforestation consortium
RF	Area redistribution factor
RPR	Residue–to–product ratio
RSD.TYP	Type of residue
SCL	Suitability class
C_{Land}	Annual land rental cost of biomass crop production
C_{Labor}	Annual labor wages cost of biomass crop production
CC	Carrying capacity
CNA	National agricultural census
CW	Carcass weight
d	Department
DANE	The Colombian national administrative department of statistics
DAP	Diammonium Phosphate
DEM_{FOOD}	Annual demand for food item per capita
DEM_{WOOD}	Annual demand for industrial roundwood per capita
DF	Dressing factor
DM	Dry matter
ECDBC	Colombian strategy for low carbon development
EFF	Land use efficiency of meat production
ENA	National agricultural survey
EP.CRP	Energy potential of bioenergy crops
$EP.RSD.AGR_{BIO}$	Energy potential of agricultural residues
FAO	Food and agriculture organization of the united nations
FCO	Feed composition factor
FCR	Feed conversion rate
FEDEGAN	The Colombian association of cattle breeders
GDP	Gross domestic product
SIPRA	The Colombian rural agricultural planning information system
$SP.RSD.AGR_{ECO}$	Ecological potential of agricultural residues
$SP.RSD.AGR_{THEO}$	Theoretical potential of agricultural residues
SPS	Silvopastoral system
SSP	Shared socioeconomic pathways
SSR	Self–sufficiency ratio
SYS	Fraction of domestic meat supply produced by a production system
UPRA	The Colombian rural agricultural planning unit
VS	Very suitable land
Y_{CROP}	Annual crop yield
Y_{WOOD}	Annual roundwood yield

a high geographical potential for energy crop production, based on the premise of closing the gap between current and possible yields for food and feed production in Latin America [8,11,13,31]. Nevertheless, the resolution of these assessment tools is aggregated [32], which falls short of addressing the diverse climates and land use patterns in Colombia.

On the other hand, national resource assessments have either limited their scope to residue streams and excluded land availability for energy crops [33–36], or addressed land competition between food and first generation (1G) energy crops at an average national scale [37]. Jimenez [38] estimated that increasing agricultural and livestock productivity in Colombia could reduce their land use by up to 19 Mha, compared to reference scenario. However, the scope and timeframe of their analysis were limited. Moreover, none of these assessments has estimated the potential of lignocellulosic energy crops or the cost of biomass supply.

An immense body of literature has tackled the prospects of silvopastoral systems[2] (SPS) and intensive silvopastoral systems (iSPS) in Colombia, and elsewhere in Latin America [39–42]. Based on evidence from several demonstration projects, these systems could enable the intensification of cattle production based on natural processes that promote increased productivity and resource use efficiency [43,44], improved GHG balance of livestock production [45], and enhanced provision of environmental services [28]. Although these systems have been mainstreamed in sectoral roadmaps [46] and national plans for emission mitigation and low carbon development [47], little is known about the impact of their upscaling on biomass availability. Ramirez–Contreras et al. [48] investigated such impact for one region;

[2] The SPS are “agroforestry arrangements that purposely combine fodder plants, such as grasses and leguminous herbs, with shrubs and trees for animal nutrition and complementary uses” [40]. The iSPS “combine high density cultivation of fodder shrubs (4000–40,000 plants ha^{-1}) with improved grasses, and tree or palm species at densities of 100–600 trees ha^{-1}” [40].

nevertheless, a national scale appraisal of biomass resources, considering regional differentiation of land use patterns, remains lacking.

The supply potential of biomass resources can be assessed by spatially–explicit or statistical analyses [12]. Spatially–explicit analysis can better show the distribution of the biomass potential considering location–specific biophysiological, environmental and socioeconomic conditions (e.g. Refs. [49–53]). However, it is more complex, laborious, and data intensive than statistical analyses [12]. Moreover, the propagation of errors and the limitation of input data are sources of high uncertainty; this could decrease the reliability of this method, and hence relative advantage, for long-term projections [54–56].

Statistical analysis is simpler, more transparent and less data intensive. Its level of disaggregation can adapt to the resolution of input data (e.g. Refs. [57–63]). While incapable of explicit zoning of alternative land uses, it could determine the general regionalized productivity trends, which could be suitable for long–term projections.

To use this method for the appraisal of land–based biomass, the statistical land balancing can be combined with land suitability allocation for energy crops in a hybrid approach [64–66]. However, since Colombia, and other developing countries, exhibit an increasing pressure on land, we complemented this hybrid approach with additional procedure to manage the expansion of land for different uses, at the national as well as regionalized levels, without compromising sensitive ecological areas.

The objective of this paper is to demonstrate a hybrid resource assessment and scenario analysis tool which could estimate the long–term supply potential of biomass crops and residues, their associated costs, and their regionalized distribution, for a resource–rich country like Colombia.

2. Methods and data

2.1. Conceptual framework

To assess the availability of land for bioenergy, we followed the concept of *surplus land*, as demonstrated elsewhere [8,65–69] and summarized in Appendix A. In the case of Colombia, the agricultural expansion is limited by the national *agricultural frontier*[3] (see Fig. 1). Smeets et al. [8] used a geographically optimized allocation of food crop production to the lands with better suitability conditions, based on agroecological zoning (AEZ) [70]. This approach can estimate the potential of reducing the area of land required for food production and releasing the less suitable land for bioenergy crops. However, it requires access to the land suitability overlaps between different crops at the geographical scale of this analysis.

Fischer et al. [65] calculated the land availability for energy crops in Europe using statistical land balance, based on average yields for food crops at country level. De Wit and Faaij [66] combined this top–down balance with a spatially–explicit agroecological zoning of energy crops [64], to estimate the biomass supply potential at regionalized level.

Such a hybrid approach was straight forward for the European case, since the area of land needed for agriculture was projected to decrease in all the considered scenarios. In contrast, the demand for food, and hence pressure on land, is projected to increase in developing countries like Colombia. Accordingly, the applicability of a hybrid approach to this case requires an additional procedure to manage the allocation of land for food, feed, and fiber, and possibly energy crops, while avoiding expansion into sensitive ecological zones. Therefore, we propose a regionalized statistical land balancing procedure and an allocation of soil suitability classes to the energy crops potentially grown on surplus land.

The modeling framework of this analysis can be divided into three main components (see Fig. 2):

1. Statistical land balance analysis, where the land availability for biomass is estimated (section 2.2).
2. Crop-specific allocation of land suitability classes to the available land for dedicated energy crops (section 2.3).
3. Calculation of the cost-supply potential of energy crops, based on [66], and residues, based on [71] (section 2.4).

The supply potential of biomass depends on future population growth, dietary preferences and agricultural and livestock productivity [31]. We explored these uncertain factors via a scenario analysis (section 2.5).

2.2. Regionalized statistical land balance

Section 2.2.1 describes the statistical balancing and allocation procedure for the different land use categories, while section 2.2.2 addresses the calculation of land claims by each land use category.

2.2.1. Land balance and allocation procedure

Colombia consists of 32 departments, grouped into five natural regions[4]: Andean, Amazonian, Caribbean, Orinoquía and Pacific (see the mapping in Appendix B [72,73]).

Based on the Colombian "Rural Agricultural Planning Information System" SIPRA,[5] the total surface area (A_{TOT}) of each department (d) is divided into: 1) areas within the boundaries of the national *agricultural frontier* (A_{AGF}), 2) natural forests and non-agricultural areas (A_{NFR}), and 3) legally excluded areas (A_{EXC}), which include natural and archeological protected areas (see equation (1) and the dataset in Appendix C).

For the land balance analysis, the (projected) demand for food, feed, and fiber (3F), and the associated land use – namely cropland for food and feed[6] (A_{CRP}), pasture land for feed (A_{PST}), and forestry plantation areas (A_{FRY}) – were estimated by bottom-up calculations (see section 2.2.2). The sum of these land claims that precede bioenergy (A_{3F}) is calculated by equation (2) and compared to the *frontier* limits per department (A_{AGF}).

As per equation (3), this balancing check (A_{BAL}) distinguishes between departments with positive imbalances (A_{+VE}), i.e. abundance of agricultural land after allocation of A_{3F}, and those with negative imbalances (A_{-VE}), i.e. insufficient land to meet the claims within the *frontier* limits. These imbalances are redistributed between departments, thereby resembling domestic trade. A relative redistribution factor (RF), calculated by equation (4), is applied such that the departments with more abundant land availability absorb higher shares of the shortages.

Based on this factor, a balancing redistribution area (A_{DST}) is calculated by equation (5). This area is added to A_{3F} to estimate the redistributed agricultural land claims per department A_{3F^*}, as per equation (6). For departments with shortage, A_{DST} is negative (third case of equation (5)).

The extent of redistribution depends on the total imbalances at national scale. If the total surpluses outweigh the total shortages (first case of equation (5)), then all the shortages are redistributed, and any residual surplus lands within the *frontier* are quantified by equation (7).

[3] The national *agricultural frontier* is defined by the Resolution 261 of 2018, issued by the Colombian Ministry of Agriculture [150]. The frontier comprises an official zoning of all the land available for agricultural production, i.e. food, feed, fiber, and biomass for energy purposes. The frontier limits exclude protected areas, natural forests and ecosystems with high value.

[4] For the scope of this research, islands are counted within the Caribbean region.

[5] SIPRA is managed by the Colombian "Rural Agricultural Planning Unit" (UPRA). The SIPRA database is an outcome of spatially explicit agroecological land evaluation and zoning based biophysical, social, economic and environmental criteria [151,152].

[6] Cropland included the existing feedstock for (co-)production of 1G biofuels.

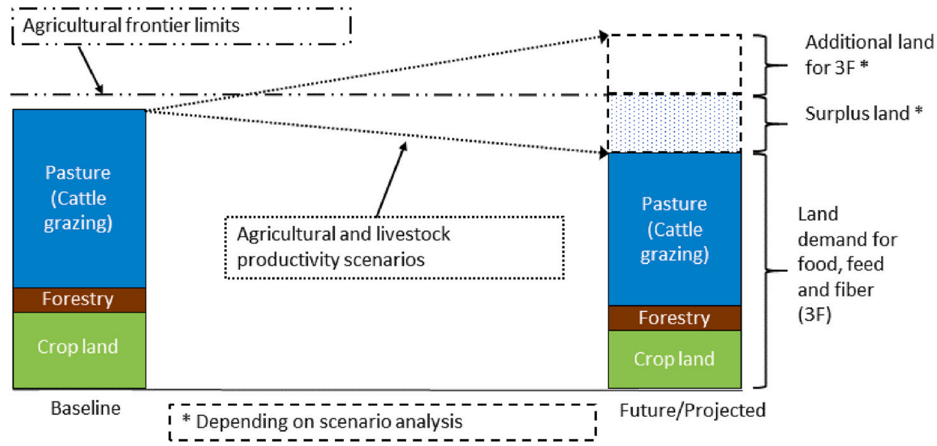

Fig. 1. Illustration of the concept of surplus land, adapted from Ref. [48]. Note that the potential for agricultural expansion is limited by the national *agricultural frontier* which is slightly higher than the agricultural land use in 2013 (not to scale).

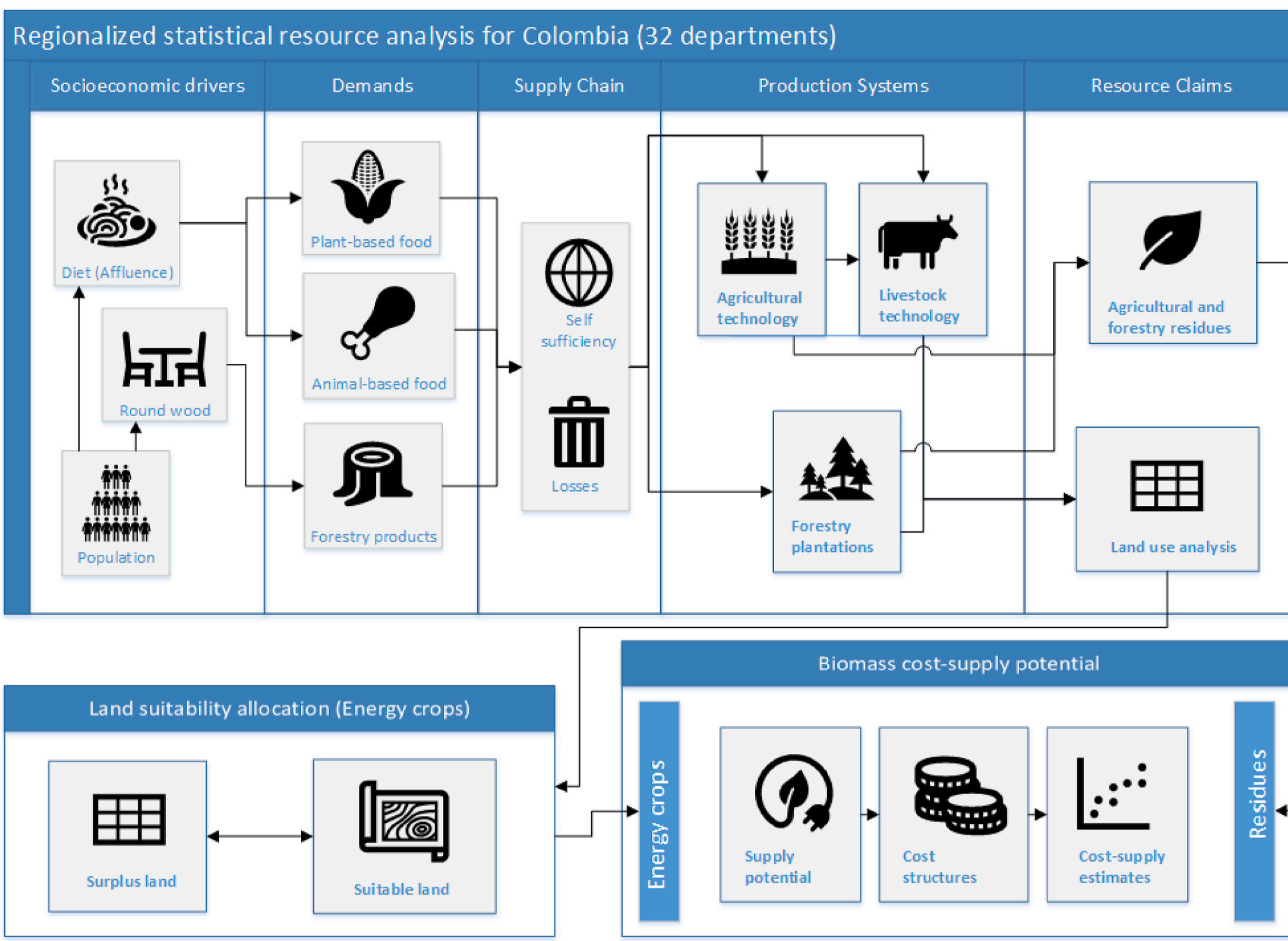

Fig. 2. Overview of the modeling framework of the analysis.

These surplus lands (A_{SRP}) could be considered for bioenergy crops, while avoiding land use competition with food or sensitive ecosystems.

On the other hand, if the total shortages outweigh the total surpluses (second case of equation (5)), then the shortages are partially alleviated by redistribution, up to the limit of the *agricultural frontier*. In this case, the residual imbalances are settled by expansion into the natural forests (A_{NFR}), i.e. deforestation. In this case, no land is available for bioenergy. This procedure is in line with observed historical deforestation patterns in Colombia, which is primarily driven by agricultural expansion [26].

The land balance analysis is calibrated to base year 2013 and applied to future projections by 2030 and 2050.

$$\sum_d A_{TOT} = \sum_d A_{AGF} + A_{NFR} + A_{EXC} \quad (1)$$

$$\sum_{d} A_{3F} = \sum_{d} A_{CRP} + A_{PST} + A_{FRY} \quad (2)$$

$$A_{BAL\ d} = |A_{AGF\ d} - A_{3F\ d}| = \begin{cases} A_{+VE\ d} & \forall A_{3F\ d} \leq A_{AGF\ d} \\ A_{-VE\ d} & \forall A_{3F\ d} > A_{AGF\ d} \end{cases} \quad (3)$$

$$RF_d \begin{cases} \dfrac{A_{+VE\ d}}{\sum_{d} A_{+VE\ d}} & \forall A_{+VE\ d} \\ 0 \quad \forall A_{-VE\ d} \end{cases} \quad (4)$$

$$A_{DST\ d} \begin{cases} RF_d \times \sum_{d} A_{-VE} & \forall \sum_{d} A_{+VE} \geq \sum_{d} A_{-VE} \\ RF_d \times \sum_{d} A_{+VE} & \forall \sum_{d} A_{+VE} < \sum_{d} A_{-VE} \\ -A_{-VE\ d} & \forall A_{-VE\ d} \end{cases} \quad (5)$$

$$A_{3F^*\ d} = A_{3F\ d} + A_{DST\ d} \quad (6)$$

$$A_{SRP\ d} = A_{AGF\ d} - A_{3F^*\ d} \quad (7)$$

2.2.2. Land use of food, feed, and fiber production

The production of food ($PROD_{FOOD}$) per item is calculated by the projected annual food demand per capita (DEM_{FOOD}), population (POP), supply chain losses ($LOSS$), and self-sufficiency ratio (SSR) – the relative contribution of domestic production to the demand (see equation (8)). We considered 16 vegetarian and animal products, owing to their major contribution to the agricultural output and land use in Colombia (see Table 1).

The land use associated with animal products was determined by the cropland and pasture land required to supply the feed for animals [65]. The area of cropland needed for food and feed crops (A_{CRP}) is calculated by the respective crop production quantity ($PROD_{CROP}$) and yield (Y) (see equation (9)). Current yields were retrieved from official statistics [74] (see departmental data in Appendix E). Future projections per scenario are explained in section 2.5.

With regard to feed calculation, the livestock was divided into monogastric animals, i.e. pigs and poultry, and ruminants, i.e. cattle, owing to their distinct feed requirements[7] [67].

Considering ruminants, the Colombian cattle sector is represented by three main production systems: a traditional extensive system based on grazing of natural pastures (low technology), an improved extensive system based on grazing of managed pastures (intermediate technology), and a semi-intensive system based on grazing of managed pastures and forage supplements (high technology) [29,75]. The potential upscaling of (i)SPS is considered in scenario analysis (section 2.5). The extensive grazing systems account for more than 90% of the domestic meat supply [75]. This can explain the low productivity of the Colombian cattle ranching [28], which is indicated by an average national CC of 0.6 LAU ha^{-1} [29], and a land use efficiency of meat production (EFF) below 100 kg_{LW} ha^{-1} [76].

Based on current national and departmental productivity data, we estimated the CC and EFF per production system in each department. The national data included the contribution of each production system to the domestic meat supply (SYS), the final live weight per production system (LW), a dressing factor (DF) – i.e. the edible fraction of LW, and the extraction rate – i.e. the fraction of the cattle population slaughtered per year (see Table 2). The departmental data included the cattle population, herd structure, and the pasture land use (see Table 2 and Appendix F). For future scenarios, we analyze the potential evolution of alternative intensification pathways, where A_{PST} is calculated by equation (10) (see section 2.5).

In terms of monogastric livestock, the demand for feed crops ($PROD_{FEED}$) is calculated by the supply of monogastric product ($PROD_{MONO}$), the feed conversion rate (FCR) – i.e. the dry matter feed intake per unit carcass weight (CW) edible product, and the feed composition factor (FCO) – i.e. the share of each feed crop in the total feed intake per livestock type (see equation (11) and Table 2).

In relation to the land use for fiber, A_{FRY} is calculated by the per capita demand for industrial roundwood (DEM_{WOOD}), POP, SSR and the yield of commercial forestry plantations (Y_{WOOD}) (see equation (12) and Table 1).

$$PROD_{FOOD} = DEM_{FOOD} \times POP \times (1 + LOSS) \times SSR \quad (8)$$

$$A_{CRP} = PROD_{CROP} \times Y_{CROP}^{-1} \quad (9)$$

$$A_{PST} = PROD_{BEEF} \times SYS \times DF^{-1} \times EFF^{-1} \quad (10)$$

$$PROD_{FEED} = PROD_{MONO} \times FCR \times FCO \quad (11)$$

$$A_{FRY} = DEM_{WOOD} \times POP \times SSR \times Y_{WOOD}^{-1} \quad (12)$$

2.3. Land suitability allocation

As explained above, our statistical land balancing approach falls short of prioritizing the allocation of food production to the lands of the highest soil quality, as proposed by other studies (e.g. Smeets et al. [8]). However, it could indicate the general potential for agricultural productivity increase per region on the long-term. Accordingly, we applied a ‘food first’ principle by ensuring that the demand for food, feed and fiber is met prior to any bioenergy crop production. However, we consider that the question of whether to grow food or biomass crops in a location of a given land quality is determined by farmers’ choices.

In practice, we handled land suitability via a two-step protocol (see Fig. 3). First, the surplus land per department was estimated by the statistical land balancing approach (section 2.2), based on average crop yields per department. Second, the surplus land was disaggregated into suitability classes solely for the energy crops considered in the analysis.

Datasets of land suitability per department were retrieved from SIPRA [100] and consortium CUE [101] (see Appendix G), distinguishing between four classes: Very suitable (VS), Moderately suitable (MS), Marginally suitable (GS), and Not suitable (NS). The disaggregation was conducted based on two rules:

- the area of land available for biomass (A_{BIO}) is restricted to that of the surplus land (A_{SRP}) and the total suitable land for bioenergy crops (A_{SUT}), whichever smaller; where the latter is the sum of the areas of lands of the VS, MS, and GS suitability classes (SCL).
- the disaggregation of A_{BIO} maintains the same proportions of each suitability class with respect to A_{SUT}.

2.4. Biomass cost-supply potential

Sections 2.4.1 and 2.4.2 explain the assessment of energy crops and residues potential, respectively.

2.4.1. Dedicated energy crops

The supply potential of energy crops ($EP.CRP$) per land suitability class was calculated by the corresponding area of available land (A_{BIO}), associated yield (Y), moisture content (M), lower heating value (LHV) and a harvesting index (HI) – i.e. the fraction of product compared to the whole plant on mass basis, for yields reported on product basis (see equation (13), adapted from de Wit and Faaij [66]). We considered three energy crops for the analysis (see Table 3). Sugarcane and oil palm are currently used for biofuels in Colombia. Eucalyptus (grandis), currently grown for roundwood, is taken as representative of woody biomass.

[7] Where monogastric animals can rely on feed crops for nutrition, ruminants require forage from pastures or crop residues, possibly supplemented with crop-based feed depending on the production system.

Table 1
Baseline projections of food and industrial roundwood demand, self-sufficiency, losses, and population.

Food demand [a] (kg cap^{-1} y^{-1})	2013	2030	2050	Self-sufficiency – SSR (–)	Calibration factor (–)	Losses (%)
Meat						
Bovine [b]	16.4	19.1	21.5	1.05	0.9	22%
Pork	6.5	7.6	8.5	0.77	1.5	
Poultry	27.6	32.1	36.2	0.96	1.2	
Cereals						
Rice (milled)	28.0	28.8	29.2	0.90	1.0	20–28%
Wheat	29.8	30.6	31.0	0.01	1.0	
Maize	30.2	31.0	31.4	0.33	0.8	
Roots and tubers						
Potato	33.5	33.5	34.0	0.95	0.7	40%
Cassava	38.5	38.5	39.1	0.99	1.2	
Sugars						
From sugarcane	33.2	33.2	32.4	1.24	1.0	28%
From jaggery (panela)	24.5	24.5	23.9	1.00	0.9	
Vegetable oils						
Palm oil	6.9	7.7	8.1	1.06	1.1	18–19%
Soybean oil	5.7	6.3	6.7	0.23	1.2	
Others						
Banana	10.6	11.4	12.1	3.80	3.1	55%
Plantain	53.1	57.4	61.0	1.02	1.0	
Coffee	1.7	1.8	1.9	7.42	1.4	19%
Cocoa	0.90	1.00	1.00	1.04	0.8	
Industrial roundwood demand [c] (m^3 cap^{-1} y^{-1})	0.11	0.16	0.16	0.73		
Population [d] (millions)	47.3	56.5	62.9			

[a] References for food demand: Current food consumption per capita was retrieved from the national food balance reported by the Food Agricultural Organization (FAO) statistics [77]. Baseline diet per capita projections were based on the growth rates per commodity group for Latin America and Caribbean, reported by Alexandratos and Bruinsma [78]. For the scenario analysis see section 2.5. The SSR per food commodity was calculated from the national trade balance in 2013, as reported by FAO statistics [77]. The SSR was assumed to remain constant for future projections. A calibration factor was used to calibrate the projections of [78] with respect to 2013 historical data [77]. Losses per commodity group were based on constant estimates for Latin America and Caribbean, retrieved from FAO [79]. For feed crops, losses at the consumption phase were excluded.

[b] The scope of animal products in this analysis is limited to meat. In Colombia, the dairy cow population is small and breeding of cows for double purpose is a common practice.

[c] The demand for industrial roundwood and the self-sufficiency ratio are based on the "commercial potential of reforestation" consortium (PROFOR) [80]. The average yield of roundwood production from forestry plantations is 25 m^3 ha^{-1} based on PROFOR [81].

[d] Current population was retrieved from the World Bank [82]; the baseline projection was based on the Shared Socioeconomic Pathways (SSP) database, SSP2 scenario [83,84]. The departmental distribution is based on the national administrative department of statistics (DANE) [85] (see the dataset in Appendix D). For the scenario analysis see section 2.5.

The cost structure of crops production (C_{CRP}) included land rental (C_{Land}), fertilizer use ($C_{Ferti.}$), labor (C_{Labor}), and capital & other costs ($C_{Capital}$) (see equation (14) and the main data for Colombia in Table 4). Considering land, C_{Land} per suitability class was calculated by the corresponding A_{BIO} and the annual rental prices per hectare (P_{Land}) (equation (15)). With respect to fertilizers, $C_{Ferti.}$ per suitability class was calculated by the corresponding A_{BIO}, the crop-specific nutrient input per hectare (N) and the corresponding price ($P_{Ferti.}$) (equation (16)). We considered three nutrient compounds commonly used in Colombia, namely Urea (46% N), Diammonium phosphate (DAP: 18% N and 46% P_2O_5), and KCl (60% K).

In relation to C_{Labor} and $C_{Capital}$, these were based on Colombian crop-specific data [81,102,103]. The capital cost of establishment includes land preparation, (irrigation) infrastructure and mechanization, among others. Other expenses represented administrative and contingency costs.

$$EP.CRP_{crop,\ SCL} = A_{BIO\ SCL} \times Y_{crop,\ SCL} \times \left(1 - M_{crop}\right) \times LHV_{crop} \times HI_{crop}^{-1} \tag{13}$$

$$C_{CRP} = C_{Land} + C_{Ferti.} + C_{Labor} + C_{Capital} \tag{14}$$

$$C_{Land\ SCL.} = A_{BIO\ SCL} \times P_{Land\ SCL.} \tag{15}$$

$$C_{Ferti.\ SCL} = A_{BIO\ SCL} \times N_{SCL} \times P_{Ferti.} \tag{16}$$

2.4.2. Agricultural and forestry residues

Considering agricultural residues, the theoretical supply potential ($SP.RSD.AGR_{THEO}$) per department on wet mass basis was calculated by $PROD_{CROP}$ and the residue–to–product ratio (RPR) (see equation (17)). The RPR was empirically calculated as a function of yields where such correlations could be established and otherwise assumed constant [71] (see Table 5). The ecological potential ($SP.RSD.AGR_{ECO}$) was calculated by equation (18), considering the minimum amount of residues required to stay at the fields to maintain soil organic carbon (2.5 t_{wet} ha^{-1}) [71]. Finally, the bioenergy potential of available agricultural residues potential ($EP.RSD.AGR_{BIO}$) was calculated based on the ecological potential, moisture and heat content per type of residue (equation (19)).

Regarding forestry residues, the theoretical potential included field logging of commercial forestry plantations, as well as sawmilling residues of industrial wood. The ecological potential was determined as a fraction of the theoretical potential, assuming that 40% of the residues stay in the field [71]. The ecological potential of field residues was assumed to be available for bioenergy, while process residues were considered to be utilized by their existing markets [33].

The cost structure of agricultural residues included harvesting, operations, storage and drying and transport; whereas that cost of forestry residues included forwarding, chipping and compression, additional costs and transport [71] (see Table 6).

$$SP.RSD.AGR_{THEO} = PROD_{CROP} \times RPR_{RSD.TYPE} \tag{17}$$

$$SP.RSD.AGR_{ECO} = max[SP.RSD.AGR_{THEO} - (2.5 \times A_{CRP})] \tag{18}$$

$$EP.RSD.AGR_{BIO} = SP.RSD.AGR_{ECO} \times (1 - M_{RSD.TYPE}) \times LHV_{RSD.TYPE} \tag{19}$$

2.5. Scenario analysis

The availability of biomass depends on several uncertain factors, the

Table 2
Overview of the livestock production system definitions, efficiency parameters and their current values.

	Cattle production systems per level of technology [a, b]			Pig meat [c]	Poultry meat [c]
	Low	Medium	High		
Final live weight – *LW* (kg)	383	420	450	101	2.3
Carcass weight – *CW* (kg)				79	2.0
Dressing factor – *DF* (–)	0.53				
Extraction rate (–)	0.20				
Feed conversion rate – *FCR* ($kg_{FI,DM}$ kg_{CW}^{-1})				6.1	4.5
Feed composition – *FCO* (%)	Natural grasses (100%)	Improved grasses (100%)	Improved grasses (70%) and forage supplements (30%)	Maize 90% Soybean 10%	Maize 33% Sorghum 33% Soybean 33%
Contribution of production systems to meat supply – *SYS* (%)	45%	49%	6%		
Carrying capacity – *CC* (LAU ha^{-1})	0.4	0.9	2.8		
Land use efficiency of meat production – *EFF* (kg_{LW} ha^{-1})	39	96	330		

[a] The cattle production systems are defined, based on Mahecha et al. [75] and Delgado Rodruguez [86], as follows:• Traditional extensive: A pastoral system, where the nutrition of cattle is mainly based on grazing of natural pastures. This low technology system is a proxy for small scale farming, with minimal use of animal breeding and disease control.• Improved extensive: A pastoral system, based on partially managed grasses, use of weed control and fertilization. It entails an intermediate technology system with partial use of preventive health management, selective breeding and artificial insemination.• Supplemented semi-intensive: A mixed system, based on highly managed grasses (frequent fertilization and/or irrigation) supplemented with feed crops and residues. This represents a high technology system: full use of preventive health management, selective breeding, and artificial insemination.

[b] References for cattle production: the *LW* and *FCO* are based on Ramirez-Contreras et al. [48]; the *DF* and extraction rate are retrieved from Colombian association of cattle breeders (FEDEGAN) [87]; and the *SYS* is based on Mahecha et al. [75]. The cattle population and the herd distribution per department are based on FEDEGAN and the Colombian ministry of agriculture (MADR) [74,88,89] (see Appendix F). The baseline pasture land use per department is based on the national agricultur[c]l survey (ENA) [90] and the national agricultural census (CNA) [91], both reported by DANE (Appendix F). The reference *CC* per department is calculated by the reference cattle population and reference pasture land use, and crosschecked with the values reported by FEDEGAN for selected departments [92]. The *CC* per production system per department was used to calibrate the departmental cattle population and land use, and the national average CC per production system [75], within an error margin of 5%. The average national CC and EFF per production system are based on own calculations, with a national average *EFF* of 60 kg_{LW} ha^{-1}.

[c] The Colombian pig sector includes extensive and (semi-) intensive production systems [86], where the intensive system represents more than 62% of the national pig population [93]. For simplification, we used an overall *FCR* for pig meat and poultry meat based on current values in Central and South America, as reported by Mekonnen and Hoekstra [94]. These values are in line with current values for Colombia reported by O'Brien et al. [95]. The live and carcass weights (*LW* and *CW*) are retrieved from the national administrative department of statistics (DANE), for pigs [96] and poultry [97]. The *FCO* for pigs and poultry is based on Campabadal [98] and DANE [99], respectively.

most critical of which are socioeconomic projections and the productivity of land use sectors [12]. We addressed them via a scenario analysis [121], using the storylines and data of the Shared Socioeconomic Pathways (SSP) framework [122]. We focused on three scenarios (SSP1-3) which sufficiently cover wide range of uncertainty.

SSP1 depicts a progressive world with low socioeconomic challenges to climate change mitigation and adaptation. In the case of Colombia, this reflected upon accelerated demographic transition, increased low carbon economic growth, and enhanced agricultural and livestock productivity. By contrast, SSP3 projects a regionalized world which faces high challenges to mitigation and adaptation. For Colombia, these challenges manifest in a fast-growing population, modest economic growth, and slow technological change, including the agricultural sector. In between, SSP2 presents a "middle of the road" scenario with moderate challenges and future projections that stem from the extrapolation of current trends.

These storylines were quantified by socioeconomic, agricultural and livestock productivity factors. With regards to socioeconomic factors, the main considered variables are population growth and dietary preferences (affluence), led by income growth [123] (see Table 7). Considering agricultural productivity, the yield projections were estimated by analysis of historical data and benchmarking highest yields in Colombian departments and elsewhere (see Table 8).

With respect to livestock productivity, the *EFF* projections of cattle production are based on Colombian studies [41,42,44,45] (see Table 9). The SSP3 scenario represents a conventional intensification pathway, where the productivity of intermediate technology converges to current level of high technology monoculture pasture management. The SSP2 scenario depicts an upscaling of (i)SPS cattle breeding, in line with the Colombian nationally appropriate mitigation actions (NAMAs) target for the bovine sector, which is roughly 1.3 and 0.4 Mha of land for livestock production through SPS and iSPS, respectively, based on the Colombian strategy for low carbon development (ECDBC) [47]. The SSP1 scenario projects wider upscaling of SPS and iSPS cattle ranching, thereby achieving higher productivity than that in the SSP2 scenario. Considering monogastric animals, the *FCR* projections are based on the estimates of Mekonnen and Hoekstra [94], for South America and other regions.

3. Results

Section 3.1 provides an overview of the land use balance and availability of surplus land. Section 3.2 illustrates the regional distribution of the surplus land. Section 3.3 demonstrates the availability of residues. Section 3.4 sketches the spatial distribution of the supply potential of energy crops and residues. Section 3.5 outlines the cumulative cost–supply potential of biomass resources.

3.1. National land use balance

Fig. 4 illustrates the national land balance projections for the AFOLU sectors. In 2013, the land occupancy of the AFOLU sectors exceeded 90% of the total area designated for agricultural activities, i.e. the national *agricultural frontier*. The main contributor to this occupancy (about 87%) was the production of bovine meat through extensive grazing of pasture. Despite the net positive availability of land at national level, some departments exhibited local imbalances, which manifested in deforestation (see Fig. 4). These imbalances, at a departmental level, were caused by the land use for grazing pasture, whether solely or combined with

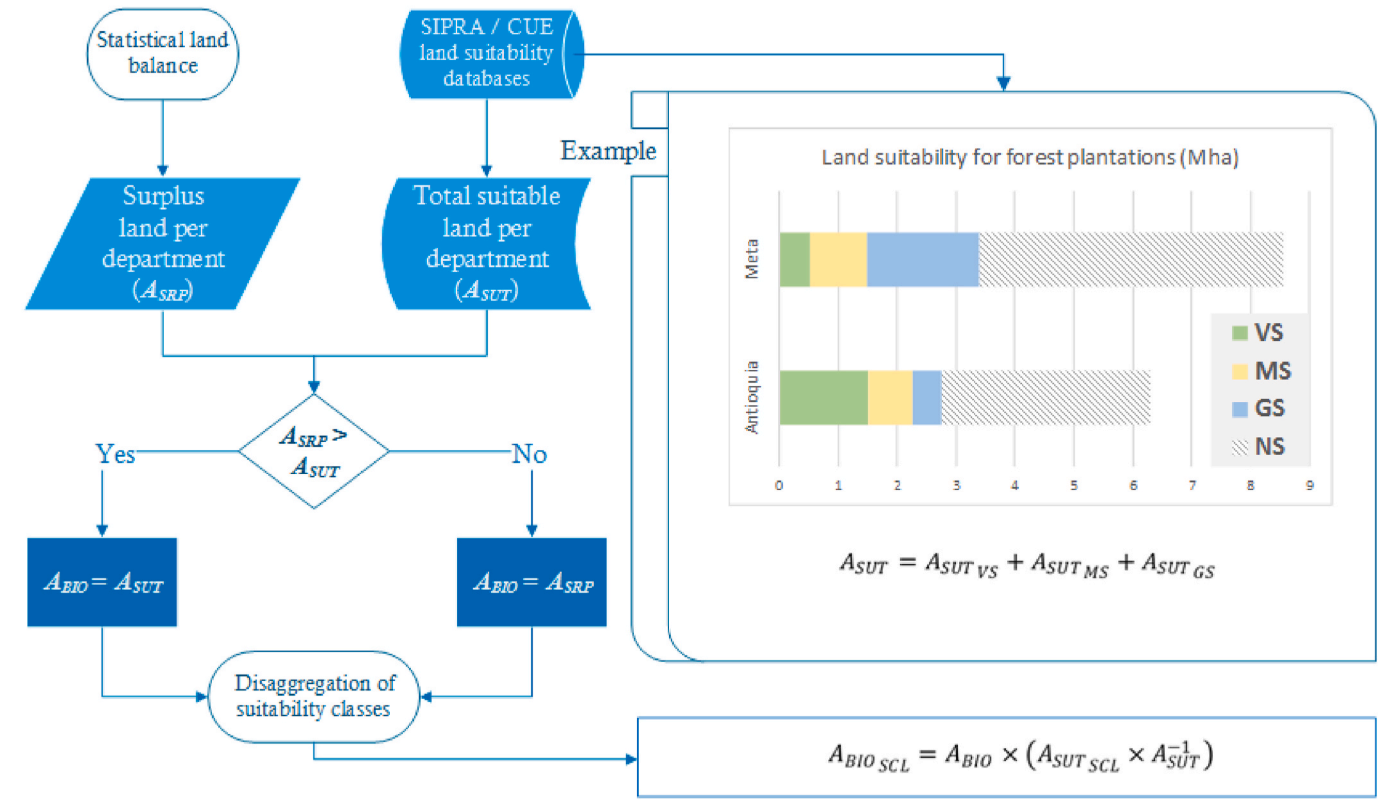

Fig. 3. Illustration of the land suitability allocation protocol.

Table 3
Yields, moisture content, caloric values (on LHV basis) and harvesting index of the assessed crops.

Crop	Attainable yield – Y [a]	Harvesting index – HI [b]	Moisture – M [c]	Lower heating value – LHV_{DM} [d] (GJ t^{-1})
Eucalyptus	29 m^3 ha^{-1}	1.0	10%	17.6
Palm Oil	5.3 t ha^{-1} oil	0.21	59%	27.1
Sugarcane	112 t ha^{-1} fresh cane	1.0	72%	17.4

[a] Yields corresponding to the VS, MS, and GS suitability classes were taken as 100%, 60% and 40% of the maximum attainable yield (Y), respectively, following the AEZ methodology [70]. For palm oil and sugarcane, Y was based on national weighted averages of the high yields scenario by 2050 (section 2.5). Regional yields of eucalyptus were based on PROFOR [81]. The specific weight of woody biomass was taken as 0.725 t_{DM} m^{-3} [33].
[b] Reference: Palm oil extraction per fresh fruit bunch, based on Garcia-Nunez et al. [104].
[c] Reference: Eucalyptus [105]; Sugarcane [106]. The remaining 28% is divided into 14% sugar and 14% fibers; Palm oil is based on Garcia-Nunez et al. [104]. The remaining 41% is divided into 21% oil, 8% empty fruit bunch, 8% fiber and 5% shell.
[d] Reference: Eucalyptus and sugarcane cane are based on [106]. The energy content of sugarcane corresponds to the LHV of its dry sugar and fiber constituents (17 GJ t^{-1} and 17.8 GJ t^{-1}, respectively). Likewise, the energy content of palm oil fresh fruit bunch, calculated based on [33,104], corresponds to the LHV of its dry constituents (36 GJ t^{-1} for crude palm oil, 17.7 GJ t^{-1} for empty fruit bunch, 17.9 GJ t^{-1} for fiber, and 17.7 GJ t^{-1} for shell).

other land uses, exceeding the respective *frontier*. A notable example is La Guajira, where the bovine *CC* was below 0.2 LAU ha^{-1} and the imbalance exceeded 0.8 Mha.

For future projections, avoiding deforestation constituted a precondition for any surplus land availability. In all scenarios, the extensive grazing for bovine meat production was projected to remain the most demanding use of land. Nevertheless, the extent of pressure exerted on the *agricultural frontier* varied per intensification pathway. In SSP3 scenario, limited increase in agricultural yields and conventional meat production through managed monoculture grasses could fall short of reversing the rate of agricultural expansion, driven by the demand for food, feed, and fiber. Thereby, the AFOLU sectors could be exposed to the risk of (continued) expansion into sensitive ecological zones, such as natural forests.

In contrast, the upscaling of more sustainable intensification of meat production, through (i)SPS, and achieving higher agricultural yields could help meeting the demand without further expansion of agricultural land. Accordingly, the land occupancy of the agricultural, livestock, and forestry sectors could fall below the limits of the *agricultural frontier*, saving up a surplus of land, which could be available to produce energy crops. In SSP2, such surplus of land could amount to 4 Mha by 2030, which reflects current land use policy targets (NAMA), and further to 8 Mha by 2050. Considering higher ambitions, as reflected in SSP1, up to 7 Mha and 14 Mha of surplus land could be available by 2030 and 2050, respectively.

3.2. Regional availability of surplus land

Fig. 5 illustrates a pareto diagram of the surplus land availability per department. In all scenarios where surplus land could be available, the highest potential for land availability could be observed in the eastern plain region – Orinoquía, particularly in Vichada department, followed by Meta, Casanare, and Arauca. These are rural departments that embrace 36% of the total area of the national *agricultural frontier*. The current occupancy of the AFOLU sectors in Vichada is low, which leaves a room for agricultural expansion. Moreover, the land use productivity of bovine meat in the region is low, where the *CC* is merely 0.4–0.8 LAU ha^{-1}.

On the short term (2030), above 60% of the surplus land potential could be concentrated in Vichada department. On the longer term

Table 4
Cost overview for land rental, fertilizers, labor, and capital expenditure for energy crop production.

Cost item [a]	Ranges [b]								
Land lease [c] ($ ha^{-1})	VS: 141–167 / MS: 130–154 / GS: 119–141								
Fertilizer cost [d] ($ (10^2 kg)$^{-1}$)	Urea: 54–68 / DAP: 62–81 / KCl: 61–71								
Fertilizer use per crop and suitability class [e] (kg ha^{-1})	**Eucalyptus**			**Palm oil**			**Sugarcane**		
	VS	*MS*	*GS*	*VS*	*MS*	*GS*	*VS*	*MS*	*GS*
• Urea	254–281	297–328	339–375	148–163	347–348	546–604	250–445	343–539	437–633
• DAP	142–157	166–183	189–209	–	–	–	–	52–58	104–115
• KCl	39–57	77–114	228–286	140–154	343–380	547–605	–	65–71	129–143
	Eucalyptus [f]			**Palm oil** [g]			**Sugarcane** [h]		
Labor ($ ha^{-1}, $ t^{-1} *)	30 *			202			91		
Capital ($ ha^{-1})	290			710–1010			1110		
Other ($ ha^{-1})	108			118–147			112		

[a] All costs are standardized and indexed to USD_{2013} values.
[b] The corresponding land rental cost and fertilizer price per department are reported in Appendix H.
[c] Reference: own calculation based on a representative "opportunity cost of land" of 167 $ ha^{-1} from a study on palm oil production in Colombia (Moseuqera et al. [107,108]). This figure is allocated to suitability classes and departments based on the ratings of the latter in the human development index (HDI) [109]. The HDI is an indicator of how developed an area or country is according to factors such as life expectancy, education, and per capita income. The allocation procedure is as follows:• The "opportunity cost" was allocated to the VS class of the department with the highest HDI rating. The cost of VS land in other departments corresponded to their HDI ratings in relation to the highest.• The difference between the most and least expensive departmental lands in the VS class was taken as the difference between costs of the VS and GS soil classes in each department.• The cost of the MS land was considered the average between VS and GS.
[d] Reference: based on DANE & MADR [110], with regional allocation for departments with unreported data. See more details and the departmental data in Appendix H.
[e] References: Own calculation based on Colombian data [111–115]. The relation between input requirements and yields was established in two steps. First, the recommended nutrient application per hectare was estimated as a range for each energy crop and SCL. Second, within each SCL, the fertilizer input range was linearly allocated to departments in proportion to their yields, such that the department with the highest yield requires the highest fertilizer input. Where no intervals were found in literature, upper and lower bounds were constructed by a variation of 5% for the reported values.
[f] For eucalyptus, the main reference is PROFOR [81].
[g] For palm oil, the cost of labor is based on DANE [102], while the capital and other costs are based on Mosquera et al. [107,108].
[h] The reference for sugarcane is DANE [103]. The cost range in the case of the capital and other costs of palm oil reflect the difference between high and intermediate levels of input and management, where the cost of the former is about 30% higher. In contrast, the capital and other costs of sugarcane and eucalyptus were based on current practices, which we considered as intermediate technology. Accordingly, like palm oil, we assumed that the cost of high technology production of sugarcane and eucalyptus would also be about 30% higher than the respective intermediate technology.

(2050), the surplus land could be more distributed, owing to the increased land use productivity in the other departments. Nevertheless, with an intermediate rate of productivity increase (SSP2), about 70% of the surplus land could remain within the four Orinoquía departments. Considering a higher rate of productivity (SSP1), the contribution of Orinoquía could fall to 50%, as more land could be available in the Andean and Caribbean regions.

3.3. Supply of agricultural and forestry residues

Fig. 6 shows the uses and availability of residues. In the base year, the theoretical potential of agricultural and forestry residues was estimated at 440 PJ. Of this potential, at least 19% was deemed necessary to stay in the field to maintain soil organic carbon. By 2050, the theoretical potential is projected to increase by 20%, 30% and 44% in SSP1, SSP2 and SSP3, respectively. The main driver of this increase is the growing production volumes of the main products. Despite the growth of the theoretical potential, the minimum fraction of residues required for soil replenishment is projected to decrease to 15%, 16% and 17% in SSP1, SSP2, and SSP3, respectively. These reductions reflect the effect of achieving higher yields, thereby reducing the surface area of productive land fields, where residues are required to stay. Moreover, about 3% of the residues, which are generated at sawmills, could be required for other uses. Accordingly, the available potential of residues is projected to reach about 435 PJ, 465 PJ, and 505 PJ in SSP1, SSP2, and SSP3, respectively.

3.4. Spatial distribution of biomass resources

Fig. 7 shows the spatial distribution maps of the energy crops and residues, in terms of the supply potential (a), and the cost of supply (b). The maps focus on the SSP1 2050 scenario, which portrays the highest distinction between departments.

Regarding energy crops, the supply potential could be highest in the Orinoquía eastern plains, owing to their capacity for generating surplus land. This region could provide half of the potential for eucalyptus and oil palm, and about 40% for sugarcane.

Remarkably, some departments in the Andean region (Antioquia and Santander) and the Caribbean region (Cesar, Magdalena and Cordoba) demonstrated a competitive supply potential of energy crops than departments in Orinoquía (Arauca and Casanare), despite the lower availability of surplus land in the former. This is mainly due to the soil suitability in Orinoquía being much lower than in the Andean and Caribbean regions. Thus, the achievable yields in these regions could, at least partially, compensate for the limited availability of surplus land.

Considering the cost of supply, some departments in the Andean, Caribbean, and Orinoquía regions could stand out as promising production centers of low cost perennial crop value chains. A prominent example is Vichada (Orinoquía), where a very high potential (>400 PJ) of woody biomass and oil palm could be available at a low (<10 $ GJ^{-1}) and intermediate (10–15 $ GJ^{-1}) production cost, respectively. Moreover, Meta (Orinoquía) and Antioquia (Anean), could become high supply centers (>200 PJ each) of woody biomass and sugarcane at a cost below 10 $ GJ^{-1}. The production of oil palm in these departments could be considerable, however with a trade–off between the supply potential and cost.

Furthermore, some other could have an intermediate supply potential (100–200 PJ) at a low cost (<10 $ GJ^{-1}). Notable examples of this category are Santander (Andean) for all the considered crops; Arauca and Casanare (Orinoquía) and Magdalena (Caribbean) for woody biomass and sugarcane; and Cesar (Caribbean) for sugarcane and oil palm.

With respect to agricultural and forestry residues, the main supply centers could be found in the Pacific region, particularly in Valle del Cauca and to some extent Cauca departments, where the largescale sugarcane industry is concentrated. Moreover, the Andean departments

Table 5
Types of residues, residue to product ratio, physical properties (moisture and density) and lower heating values.

Crop	Residue type	Residue–to–product ratio – *RPR* Value — [formula] [a] (–)	Moisture – *M* (%)	Lower heating value – *LHV* (GJ t^{-1})
Agricultural residues				
Rice	straw	1.94 [b] — [−0.925 × ln(*Y*) + 3.11] [c]	9% [d]	17.26 [d]
	husk	0.25 [b]	11% [d]	16.42 [d]
Wheat	straw	1.30 [e] — [−0.281 × ln(*Y*) + 1.45] [c]	9% [d]	18.20 [d]
Maize	stalks	1.31 [b] — [−0.138 x ln(*Y*) + 1.23] [c]	8% [d]	17.55 [d]
	cob	0.27 [b]	8% [d]	16.15 [d]
	husk	0.20 [b]	7% [b]	16.83 [b]
Potato	straw	0.96 [e]	11% [e]	13.50 [e]
Cassava	straw	0.06 [f]	15% [f]	17.50 [f]
Sugarcane	tops and leaves	0.36 [b] — [−0.18 × ln(*Y*) + 0.60] [c]	47% [b]	17.24 [b]
	bagasse	0.31 [b]	48% [b]	17.25 [b]
Panela	tops and leaves	4.01 [g]	47% [b]	17.24 [b]
	bagasse	2.28 [g]	48% [b]	17.25 [b]
Palm oil	empty fruit bunch	0.22 [h]	65% [h]	19.27 [d]
	fiber	0.13 [h]	35% [h]	19.22 [d]
	shell	0.06 [h]	14% [h]	19.24 [d]
Coffee	stem	3.18 [b]	20% [b]	19.05 [b]
	pulp	2.33 [b]	71% [b]	16.85 [b]
	husk	0.22 [b]	11% [d]	19.71 [d]
Banana	stem	5.60 [i]	96% [i]	11.66 [i]
	leaves	0.35 [i]	83% [i]	11.37 [i]
Plantain	stem	4.04 [i]	95% [i]	10.89 [i]
	leaves	0.34 [i]	80% [i]	11.30 [i]
Forestry residues				
Forest biome		**Residue–to–product ratio – *RPR*** (–)	**Density** (t_{DM} m^{-3})	**Lower heating value – *LHV*** (GJ t^{-1})
Tropical forest wood plantation [c]		0.52 [b]	0.72 [c]	18.50 [b]

[c] The assessment of the forestry residues in this analysis is limited to those associated with industrial roundwood production; thus it can be rather conservative.

[a] For dynamic *RPR* values ($RPR_{dyn.}$), the empirical formulae were applied to crop groups and not crops. Accordingly, a calibration procedure was introduced so that the national weighted average *RPR* in the base year ($RPR_{wt.av.BY}$) matches with the national values reported in literature ($RPR_{rep.}$). The following formula was used: $RPR_{dyn.} = RPR_{uncalib.} \times RPR_{rep.} \times {RPR_{wt.av.BY}}^{-1}$. . Yields are in t ha^{-1}.

[b] Reference: Gonzalez-Salazar et al. [33].

[c] Daioglou et al. [71].

[d] TNO Phyllis database [105].

[e] Gao et al. [116].

[f] Koopmans and Koppejan [117].

[g] UPME [36].

[h] Garcia-Nunez et al. [104], and.

[i] Rodríguez Cáceres et al. [118].

of Antioquia and Santander could host another supply center owing to their high agricultural production volumes. The cost of supply could be generally low (<4 \$ GJ^{-1}) except for remote rural areas, mainly in the Amazon region.

Table 6
Breakdown of the cost structure for agricultural and forestry residues.

Agricultural residues [a]		Forestry residues [a]	
Harvest cost	57.6 \$ ha^{-1}	Forwarding	0.7 \$ GJ^{-1}
Operations (hauling, nutrient substitution)	1.8 \$ GJ^{-1}	Chipping/ compressing	1.4 \$ GJ^{-1}
Storage and drying	1.4 \$ GJ^{-1}	Additional costs	0.6 \$ GJ^{-1}
Transport [b]	0.4–0.7 \$ GJ^{-1}	Transport [b]	0.4–0.7 \$ GJ^{-1}
Total cost ranges	2.4–7.8 \$ GJ^{-1}	**Total cost ranges**	3.0–3.5 \$ GJ^{-1}

[a] Reference: Daioglou et al. [71]. The lower bound in the total cost ranges corresponds to agro–industrial residues. Costs are reported by source per unit energy on higher heating value (HHV) basis. These were converted to LHV basis based on the formula: $LHV = HHV \times (1 - M) - 2.447 \times M$ [119].

[b] For the transport of residues, a truck based system was assumed with a cost of 0.014 \$ GJ.km^{-1} [71] and an economical traveling distance range of 25–50 km [120].The distance range is allocated to the departments in inverse relation to the population density, through an exponential function [71].

3.5. Overall biomass cost–supply potential

Fig. 8 presents an overview of the national cost–supply potential for the production of alternative energy crops on surplus land (eucalyptus, oil palm, and sugarcane),[8] as well as the potential for agricultural and forestry residues associated with food and fiber production, for all scenarios by 2030 and 2050.

In the conservative land use productivity scenario (SSP3), only residues are considered since no land is projected to be available for energy crops. Their cumulative potential could amount to 500 PJ by 2050, half of which could be available at 3.1 \$ GJ^{-1} or less.

Considering the intermediate productivity scenario (SSP2), the supply of residues could be complemented with energy crops on surplus land. The cumulative potential of crops could amount up to 600 PJ on the short term (2030) and possibly double on the longer term (2050). However, most of this potential is projected to be available in the eastern region, where the soil productivity is low, and the production cost is likely to exceed 8 \$ GJ^{-1}.

Regarding the high productivity scenario (SSP1), the short–term potential for energy crops could remain concentrated in the eastern region, where the estimated production cost is costly. However, the higher availability of surplus land in this scenario, compared to SSP2, could enable a higher cumulative potential up to 1000 PJ by 2030. On the longer term, more economic potential could be identified in the Andean and Caribbean regions. Thus, a cumulative potential up to 2200 PJ could be achieved by 2050, where about half of this potential could be attained at 7 \$ GJ^{-1} or less.

4. Discussion

To the best of our knowledge, this study is one of the first attempts to: a) estimate, within a single framework, the supply potential for both energy crops on surplus land and residues in Colombia, b) consider the impacts of recent trends in livestock production and land use policies on

[8] Note that the energy content of 1G crops not only includes oil and sugar but also the associated residues. These residues are typically separated from the main product at the mills, and hence are assumed to be available at no additional cost. In this analysis, the production cost is distributed among the crops and the residues. The rationale behind this is to demonstrate an optimized use of dedicated purpose–grown crops by accounting for their total energy harvest. However, the quality of lignocellulosic residues is less than the main products and hence their valorization requires more processing.

Table 7
Projections of socioeconomic scenario variables (population, economic growth, and food demand per capita).

Socioeconomic variables	Current	SSP1		SSP2		SSP3	
	2013	2030	2050	2030	2050	2030	2050
Population [a] (thousands)	47,343	54,538	57,473	56,453	62,925	58,809	70,671
GDP PPP [a] (billion \$ y-1)	599	1147	2388	1088	1945	1046	1517
Diet [b] (kcal cap^{-1} day^{-1})	2500	2663	2835	2631	2720	2601	2584

[a] The current population and future projections are based on the World Bank [82] and the SSP database [83,84], respectively. Likewise, the current Gross Domestic Product (GDP) Purchasing Power Parity (PPP) and future projections are based on the World Bank [124] and the SSP database [83,84], respectively.

[b] The diet per capita (proxy for affluence) is presented by the aggregated nutritional value of the food items considered in this analysis (Table 1), based on the food composition factors reported by the Dutch food composition database (NEVO) [125]. The per capita diet projections (DEM_{FOOD}) are calculated as follows:• In case of SSP2, DEM_{FOOD} corresponds to the business-as-usual projections (see Table 1).• For SSP1 and SSP3, DEM_{FOOD} is calculated from that of SSP2, based on the relative differences in GDP per capita (GDP_{cap}) and an income elasticity factor of food consumption (taken as 0.14 [126]), as per the equation.$DEM_{FOOD\,SSPx} = DEM_{FOOD\,SSP2} \times \left(\frac{GDP_{cap\,SSPx}}{GDP_{cap\,SSP2}}\right)^{elasticity}$

Table 8
Current weighted average national crop yields in the base year and future projections per scenario.

Crop yields [a] (t ha^{-1})	Base year	SSP1 2050	SSP2 2050	SSP3 2050
Rice	5.0	7.7	7.3	6.8
Maize	3.5	7.0	6.1	5.2
Potato	18.6	32.2	28.5	24.8
Soy	2.7	4.0	3.2	2.5
Wheat	1.7	2.8	2.2	1.7
Sorghum	3.5	5.0	4.3	3.5
Banana	32.0	46.8	30.0	12.3
Cocoa	0.5	0.8	0.8	0.6
Coffee	0.9	1.5	1.3	1.1
Jaggery	6.0	14.7	11.0	7.2
Sugarcane	111.6	154.4	130.4	106.5
Palm oil	3.2	5.2	4.7	4.2
Plantain	9.2	17.8	14.5	11.2
Cassava	11.4	23.7	19.2	14.8

[a] Current national weighted average yields are based on MADR [74] (see departmental data in Appendix E). The attainable yields by 2050 in SSP1 were set to the highest yield recorded by any department from the historical dataset. To validate the plausibility of achieving these levels, we compared the yield growth rates per crop to the highest achieved in Latin America and globally. The yields in SSP2 represented an average case between SSP1 and SSP3. The yield projections in SSP3 were determined from historical yields by means of time series forecasting, using an exponential smoothing algorithm [127]. Historical yields were obtained from national weighted average yields of departmental production between 1987 and 2015 [74]. The nationally determined growth rates were applied to the current yields in each department.

Table 9
Livestock land use productivity and feed conversion efficiency in the base year and future scenarios.

Livestock productivity variables	Base year	SSP1 2050	SSP2 2050	SSP3 2050
<u>Bovine meat</u> [a]				
Land use efficiency of meat production – *EFF* (kg_{LW} ha^{-1})				
• Low technology	39	78	68	57
• Intermediate technology	96	342	329	329
• High technology	329	827	712	329
Dressing factor – *DF* (−)	0.53	0.57	0.55	0.53
<u>Pig meat</u> [b]				
Feed conversion rate – FCR [b] (kg_{DM} kg_{CW}^{-1})	6.1	4.1	5.2	5.8
<u>Poultry meat</u> [b]				
Feed conversion rate – FCR [b] (kg_{DM} $kg_{product}^{-1}$)	4.5	3.4	3.6	4.2

[a] References for the land use efficiency scenarios of bovine meat production systems:• The low technology system is based on extensive grazing of natural degraded pastures. This system is characterized by low density of biomass for feed, about 960 kg_{DM} ha^{-1} y^{-1}, and low daily weight gain per animal, below 0.4 kg day^{-1} [41]. The CC in this system ranges between 0.5 and 0.8 LAU ha^{-1}. The *EFF* in SSP1, SSP2, and SSP3 is based on Gaviria et al. [44], Calle et al. [41] and Cuartas et al. [42].• The intermediate technology system is based on extensive grazing of improved pastures. Compared to traditional grazing, this system exhibits higher density of feed intake, about 2900 kg_{DM} ha^{-1} y^{-1} and daily weight gain per animal of 0.6 kg day^{-1}. Thus, the CC in this system can reach between 1.5 and 2.3 LAU ha^{-1}. The *EFF* in SSP1 is based on Gaviria et al. [44], while in SSP2–3 is based on Calle et al. [41]. Apart from improved monoculture pastures, we also account for the SPS as an intermediate technology since it achieves comparable level of *CC* (2–3 LAU ha^{-1}) [47]. Despite the comparable productivity of both systems, the SPS relies more on natural processes and requires much less external input; therefore, it performs better on GHG emissions. However, the GHG balance lies beyond the scope of our study.• The high technology production in SSP1 and SSP2 is based on iSPS, which combines fodder grasses or leguminous herbs with shrubs and trees for animal nutrition [76]. This system can provide a nutritional intake of 7760 kg_{DM} ha^{-1} y^{-1} and daily weight gain per animal of 0.8 kg day^{-1} [41]. Accordingly, the corresponding CC can reach 3.5–4 LAU ha^{-1}. The *EFF* in SSP1 and SSP2 is based on Gaviria et al. [44] and Naranjo et al. [45].Regarding *DF*, the current value is based on FEDEGAN statistics [87] and is assumed to remain in SSP3 scenario. Future projections in SSP1 and SSP2 resemble current levels achieved in Argentina and Brazil, respectively, as reported by FEDEGAN [128].

[b] The *FCR* values for pigs and poultry are based on Mekonnen and Hoekstra [94]. Current level is an average value for Central and South America; whereas in SSP1, SSP2, and SSP3, it is assumed to converge towards the levels in North America, Western Europe, and world average, respectively.

the biomass potential, c) emphasize the differentiation of the potential at a departmental level, and d) account for the cost of biomass supply.

Our results show that pursuing ambitious GHG mitigation targets in the land use sector, by upscaling agroforestry production systems, could also create an opportunity for GHG mitigation in the energy sector, by increasing the availability of land to produce bioenergy crops.

In an optimistic trajectory (SSP1 scenario), up to 14 Mha of land could become available on the long term (2050). The corresponding biomass potential could reach up to 2200 PJ, exceeding present day total primary energy supply in Colombia, where half of this potential could be attainable at 7 \$ GJ^{-1} or less. In a moderate trajectory (SSP2), up to 8 Mha could be available, supporting a supply of 1200 PJ from perennial bioenergy crops. These potentials could complement the biomass potential from residues. On the other hand, pursuing a conventional pathway of agricultural production (SSP3) could lead to continued deforestation. In this case, no land would be available for bioenergy crops, and the supply potential of biomass could be limited to that of residues, about 500 PJ. On a regional level, potential supply centers could be identified in Orinoquía, Andean, and Caribbean regions for energy crops and the Pacific region for residues.

To put the results into context, we address below the limitations and uncertainties of our analysis (section 4.1), the sustainability considerations of biomass production (section 4.2), and the implications of the results for the land use and energy policy landscapes (section 4.3).

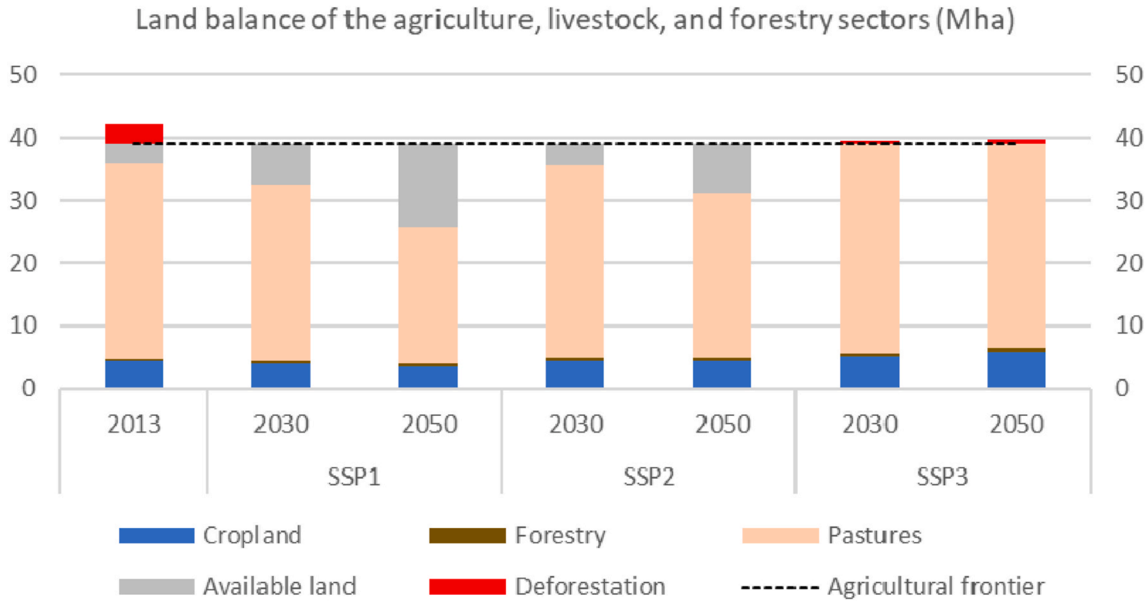

Fig. 4. Land balance of the agriculture, livestock, and forestry sectors, in relation to the agricultural frontier (Mha).

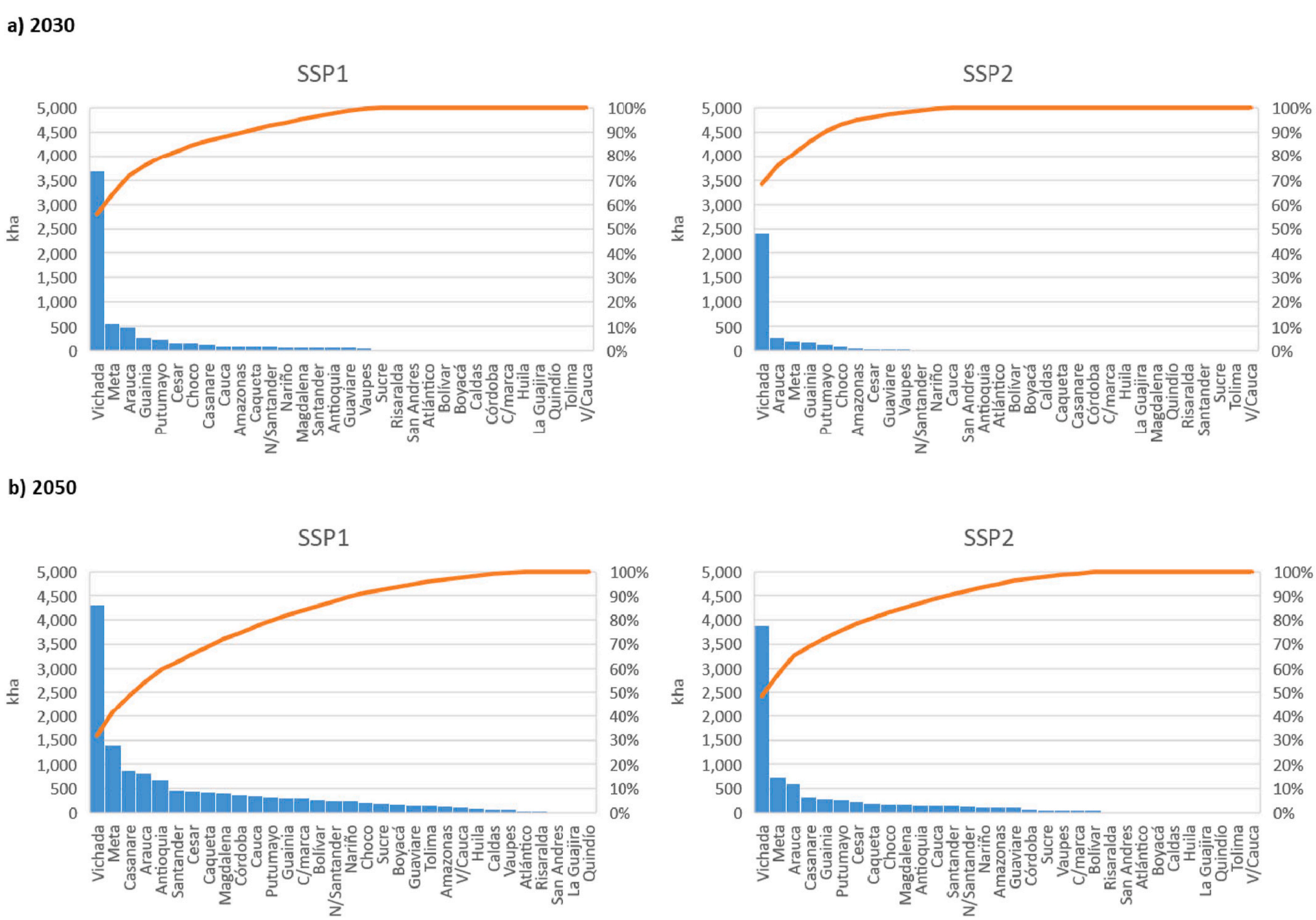

Fig. 5. Surplus land availability per department (kha) and the cumulative contribution to the total surplus land in SSP1 and SSP2 scenarios. Note that in SSP3 scenario no surplus land is projected to be available.

4.1. Uncertainties and limitations

As established earlier, the hybrid method proposed in this analysis lacks the capacity for a spatially explicit allocation of food and biomass crops. Accordingly, while meeting the 'food first' principle at a departmental level, we considered biomass production as an equal option to

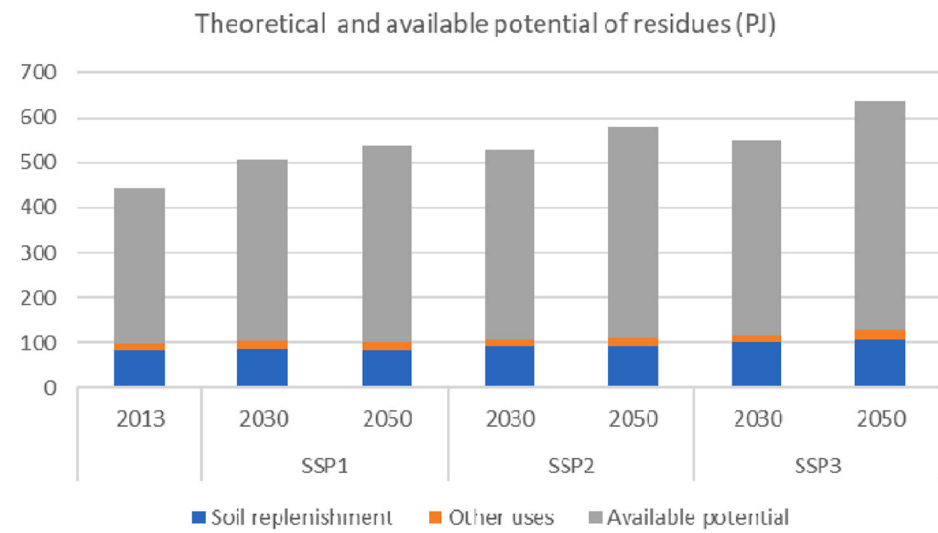

Fig. 6. Theoretical and available potential of agricultural and forestry residues (PJ).

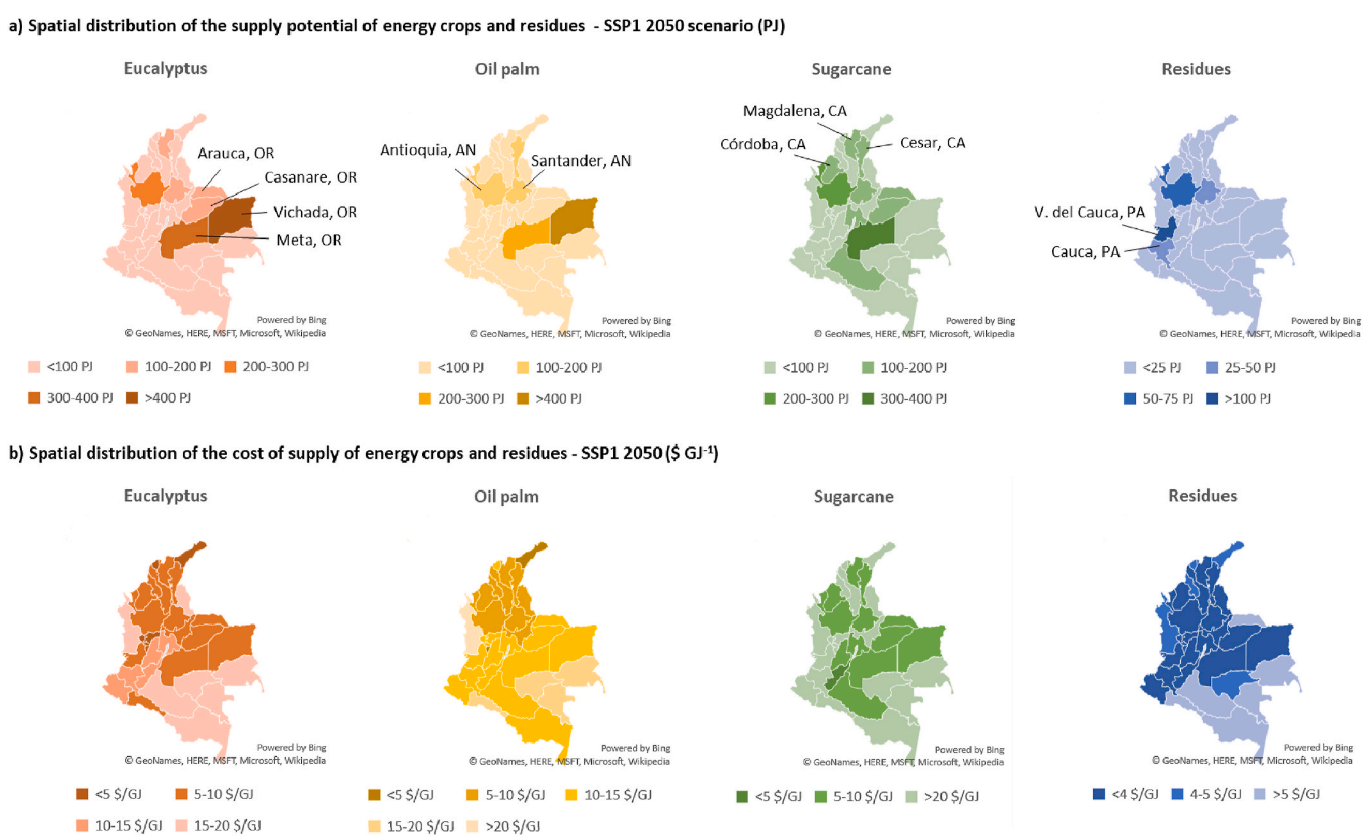

Fig. 7. a) Spatial distribution of the supply potential of energy crops and residues in SSP1 2050 scenario (PJ); and b) Spatial distribution of the cost of supply of energy crops and residues in SSP1 2050 scenario ($ GJ^{-1}); where AN: Andean region, CA: Caribbean region, OR: Orinoquía eastern plains region, and PA: Pacific region.

food crops from a farmer's perspective. Had the production of food been prioritized on the lands of the highest soil quality, following Smeets et al. [8], the land use of food would have been less. Thereby, more land would have been available for bioenergy crops, although most of which of marginal quality. These effects are counteractive, and thus are expected to have a little influence on the magnitude of the estimated biomass potential.

Reflecting on the productivity and upscaling potential of (i)SPS, Chará et al. [40] reported that the transformation of cattle ranching on degraded pastures in dry and semi–humid tropical regions in Colombia towards (i)SPS increased the productivity of meat from 85 to 126 kg_{LW} ha^{-1} to 1034–1187 kg_{LW} ha^{-1} within the span of nine years. When applied to pastures of better condition, in Mexico, the meat production increased from 341 to 2670 kg_{LW} ha^{-1}. However, the success of iSPS ultimately depends on the adequate selection of the plant species, especially the fodder shrub which represents the backbone of the system [41]. In Colombia, the combined suitability of three species of (i)SPS exceeds 10 Mha, and possibly higher when sub–optimal conditions are

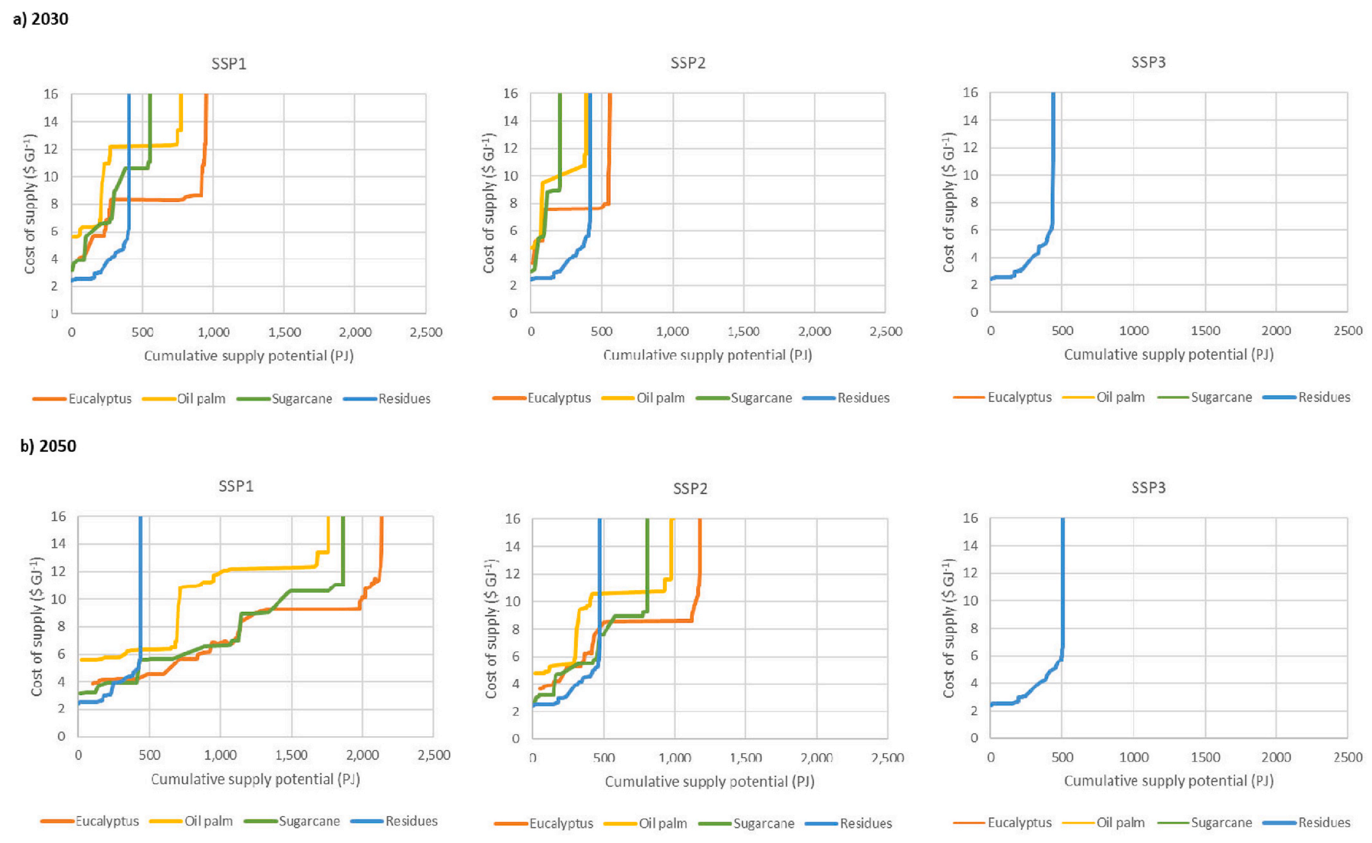

Fig. 8. National cost–supply potential of alternative dedicated energy crops on surplus land and that of the agricultural and forestry residues associated with food and fiber production, a) for 2030 and b) for 2050 scenario projections. The energy potentials of the whole sugarcane and palm oil harvest include the corresponding sugars and oils as well as the lignocellulosic material (sugarcane bagasse and oil palm fresh fruit bunches, fiber, and shells) which is usually separated in processing mills. The cost of crop supply is based on farm gate, thus excludes the cost of transport and milling.

also considered [40,47]. Accordingly, the potential for upscaling of iSPS could be realistic, although its realization will require more detailed analysis at local level.

An inherent limitation of the resource–focused bottom–up approach used in this analysis lies in its incapacity to consider indirect and induced effects beyond the defined system boundaries [32], e.g. price responses and rebound effects in interaction with agricultural and energy markets [129–131]. These feedbacks within the economic (and biophysical) system(s) could be better analyzed through CGE (and IAM) models [32].

Stringent GHG mitigation targets in line with the Paris agreement could stimulate the demand for international bioenergy trade, where Latin America is projected to become an important net exporter [132]. The capacity of bioenergy to deliver the anticipated net climate benefit in a sustainable way will require case– and site–specific investigation [133].

The role of the AFOLU sector in delivering land–based GHG mitigation and supplying biomass is closely tied to the sustainable development goals (SDGs) agenda. Frank et al. [134] found that achieving SDG goals for Zero Hunger, Clean Water and Sanitation, Responsible Production and Consumption, and Life on Land could be in synergy with GHG abatement. However, protecting highly biodiverse ecosystems could reduce the potential of biomass by up to 30%, especially in Latin America, due to the high share of dedicated energy plantations in the supply potential. Future research could explicitly address the net GHG emission savings of different land use scenarios and the role of SDGs at national level.

Considering key uncertainties, dietary choice is an important factor that was outside the scope of this analysis. As population growth tends to stabilize, the highest pressor on land is projected to be the transition towards more affluent diets, especially in emerging economies [135,136]. In this research, we explored the potential of reducing the land required for (meat–based) affluent diets by optimizing the feed composition of livestock. However, we neglected options such as shifting towards meat with a lower land requirement or towards a more vegetarian diet [137].

To understand the role of dietary changes on our results, we analyzed the effect of partial substitution of bovine meat with pig and poultry meat.[9] We compared this factor to other parameters on the demand side, supply chain, and production of bovine meat, in terms of their influence on the availability of surplus land in SSP2 2050 scenario (see Fig. 9).

The results of the sensitivity analysis suggest that dietary choice could have a crucial impact on land use, compared to other factors, where substituting 10% of the protein intake from bovine meat with pig and poultry meat could increase the land that could be released by 75%. Accordingly, reducing the consumption of bovine meat could potentially reduce the trade–off between the land use and GHG emissions of agriculture (see section 4.2), while increasing land availability for bioenergy crops or nature reserves [136,138]. These results agree with recent 'dietary shift' literature, which anticipated the transition towards healthy diets within planetary boundaries in Colombia and other developing countries, as opposed to baseline or average western diets, to achieve remarkable reductions, not only in AFOLU related GHG emissions [139], but also the respective fresh water footprint [140]. However, the question of responsible consumption extends beyond national

[9] The substitution of meat products was considered at a constant level of protein intake, based on conversion factors of 148, 108, and 104 $g_{protein}$ $kg^{-1}_{product}$ for bovine, pig, and poultry meat, respectively [153].

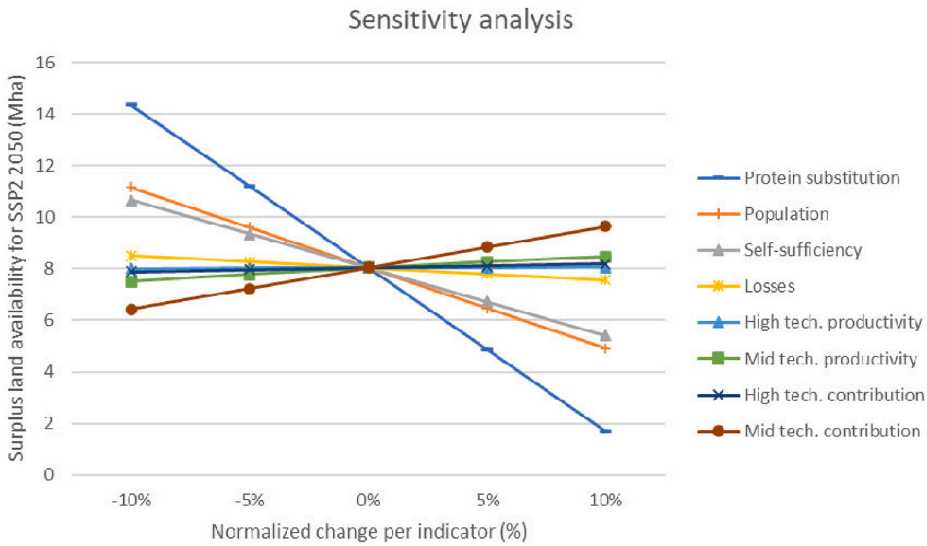

Fig. 9. Sensitivity the availability of surplus land availability to the normalized change of key demand, supply chain, and production indicators in SSP2 2050 scenario. Demand indicators include population and the substitution of protein intake from bovine meat with pig and poultry meat. Supply chain indicators include the self–sufficiency and losses of bovine meat production and consumption. Production indicators include the land use productivity of the intermediate technology (SPS) and high technology (iSPS) systems, and their respective contribution to the total meat production.

borders, where about one–third of the tropical deforestation–related emissions could be attributed to international agricultural and forestry trade [141].

4.2. *The sustainability of agricultural intensification and biomass production*

Some studies highlighted the trade–off between reducing the use of arable land, via achieving higher crop yields, and increasing the use of nitrogen fertilizer [142]. Such a trade–off could be augmented in emerging economies, owing to their transition from basic diets towards more affluence [143]. The excessive application of synthetic nitrogen could incur negative implications for water and air quality and GHG emissions [144]. These concerns also apply to the large scale production of bioenergy crops [145].

To address these sustainability concerns, we explored the potential role of livestock intensification through (i)SPS agroforestry systems. These systems rely on natural processes for increasing the productivity of forage supply for animal nutrition, thus eliminating the need for chemical fertilizer input [44]. On the contrary, these systems have been found to reduce soil erosion and improve nutrient fixation in the soil [28], recover ecological processes and biodiversity [146], and record a net negative GHG emission balance of cattle production [45].

Regarding perennial bioenergy crops, their GHG balance is much more dependent on the changes in soil carbon stock, which is influenced by site selection, than the nitrogen–induced emissions [147]. Ramirez–Contreras [48] deduced that the intensification of livestock production, through iSPS, in the Orinoquía region, and the use of surplus land for bioenergy crop production could result in carbon sequestration in the soil and a net negative GHG emission balance for the production food and bioenergy crops, compared to baseline land use patterns. This is a rather interesting outcome, considering the concentration of the biomass supply potential in this region, from a national perspective, as indicated by our analysis.

4.3. *The implications for the Colombian land use and energy landscape*

Previous assessments of the supply potential of biomass in Colombia have mostly limited their scope to residues (e.g. Refs. [33–36]). In comparison, our estimates of the residues are rather conservative. However, we argue that the potential for perennial crops, as a complementary resource that is often neglected by previous studies, could exceed the estimates of residues, including the more optimistic figures. The mobilization of such potential for bioenergy crops could provide a cost–efficient trajectory for achieving deep GHG emission reduction in the Colombian energy sector and producing biochemicals [6].

Regarding the land availability for biomass, our results show that the land use productivity potential estimated by Jimenez [38], leading to a surplus land of 19 Mha by 2030, may not be realistic within such time frame. By contrast, our projections of the current policy scenario (SSP2) are consistent with the NAMA target to reduce the GHG emissions of the bovine sector, where about 4 Mha of land is projected to be released for "other purposes" [47]. However, no direct link is established between this target and the GHG mitigation target of the energy sector. In this context, our results could help identify opportunities to synergize between the GHG mitigation and sustainable development goals of the land use and energy sectors, in relation to the development of a low carbon bio–based economy.

To realize such potential, some challenges and considerations should be addressed, including the establishment of sustainability standards that emphasize biodiversity conservation, the creation of employment opportunities, and rural development issues, particularly the investment in infrastructure and resolving land ownership issues [148]. Our analysis confirms these concerns, since it demonstrated that much of the biomass supply potential could be available in rural regions.

Further research could combine this resource–focused approach with a demand–driven approach, to analyze the potential of sustainable biomass value chains within a holistic framework.

5. Conclusion

In this paper, we demonstrated a hybrid biomass resource assessment tool of an intermediate resolution, between aggregated global assessment models and advanced spatially explicit models. Thereby, our regionalized method could provide a reasonable level of detail, compared to the former, while avoiding the complexity and data intensity of the latter models, which tend to be unreliable for long term projections.

This tool could be applied for initial screening and mapping of regions which could benefit from further detailed analysis. The administrative division could be flexibly scaled up or down, e.g. to countries within a continent, or municipalities within a province, subject to data availability. The represented land use categories could be adjusted to the case study. The modular nature of the tool enables incremental improvements and the expansion of its scope, e.g. to estimate the energy intensity and GHG balance of alternative agricultural intensification pathways.

Compared to previous hybrid assessments, we presented a novel procedure to handle the allocation of land use under conditions of expansion. This amendment increases the relevance of the hybrid approach to developing countries in demographic transition. Many of these countries, in Latin America, Southeast Asia, and sub-Saharan Africa, are in the heart of the debate over the global supply potential of biomass, the global land use–related GHG emissions, and the balance between climate change mitigation and other sustainable development goals.

Acknowledgements

Funding: This work was supported by the Netherlands Enterprise Agency (RVO) grant number TF13COPP7B.

Special thanks to Sanderine Nonhebel for her feedback and suggestions to improve this work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biombioe.2021.106096.

References

[1] V. Daioglou, J.C. Doelman, B. Wicke, A. Faaij, D.P. van Vuuren, Integrated assessment of biomass supply and demand in climate change mitigation scenarios, Global Environ. Change 54 (2019) 88–101, https://doi.org/10.1016/j.gloenvcha.2018.11.012.

[2] S.K. Rose, E. Kriegler, R. Bibas, K. Calvin, A. Popp, D.P. van Vuuren, J. Weyant, Bioenergy in energy transformation and climate management, Climatic Change 123 (2014) 477–493, https://doi.org/10.1007/s10584-013-0965-3.

[3] J. Rogelj, A. Popp, K.V. Calvin, G. Luderer, J. Emmerling, D. Gernaat, S. Fujimori, J. Strefler, T. Hasegawa, G. Marangoni, V. Krey, E. Kriegler, K. Riahi, D.P. van Vuuren, J. Doelman, L. Drouet, J. Edmonds, O. Fricko, M. Harmsen, P. Havlík, F. Humpenöder, E. Stehfest, M. Tavoni, Scenarios towards limiting global mean temperature increase below 1.5 °C, Nat. Clim. Change 8 (2018) 325–332, https://doi.org/10.1038/s41558-018-0091-3.

[4] D.P. van Vuuren, E. Bellevrat, A. Kitous, M. Isaac, Bio-energy use and low stabilization scenarios, Energy J. 31 (2010) 193–221. www.jstor.org/stable/41323496.

[5] C. Hennig, A. Brosowski, S. Majer, Sustainable feedstock potential - a limitation for the bio-based economy? J. Clean. Prod. 123 (2016) 200–202, https://doi.org/10.1016/j.jclepro.2015.06.130.

[6] A. Younis, R. Benders, R. Delgado, T. Lap, M. Gonzalez-Salazar, A. Cadena, A. Faaij, System analysis of the bio-based economy in Colombia: a bottom-up energy system model and scenario analysis, Biofuels, Bioprod. Biorefining 15 (2) (2021) 481–501, https://doi.org/10.1002/bbb.2167, bbb. 2167.

[7] S. Searle, C. Malins, A reassessment of global bioenergy potential in 2050, GCB Bioenergy 7 (2015) 328–336, https://doi.org/10.1111/gcbb.12141.

[8] E. Smeets, A. Faaij, I. Lewandowski, W. Turkenburg, A bottom-up assessment and review of global bio-energy potentials to 2050, Prog, Energy Combust. Sci. 33 (2007) 56–106, https://doi.org/10.1016/j.pecs.2006.08.001.

[9] H. Yamamoto, J. Fujino, K. Yamaji, Evaluation of bioenergy potential with a multi-regional global-land-use-and-energy model, Biomass Bioenergy 21 (2001) 185–203, https://doi.org/10.1016/S0961-9534(01)00025-3.

[10] M. Hoogwijk, A. Faaij, R. van den Broek, G. Berndes, D. Gielen, W. Turkenburg, Exploration of the ranges of the global potential of biomass for energy, Biomass Bioenergy 25 (2003) 119–133, https://doi.org/10.1016/S0961-9534(02)00191-5.

[11] T. Beringer, W. Lucht, S. Schaphoff, Bioenergy production potential of global biomass plantations under environmental and agricultural constraints, GCB Bioenergy 3 (2011) 299–312, https://doi.org/10.1111/j.1757-1707.2010.01088.x.

[12] B. Batidzirai, E.M.W. Smeets, A.P.C. Faaij, Harmonising bioenergy resource potentials - methodological lessons from review of state of the art bioenergy potential assessments, Renew. Sustain. Energy Rev. 16 (2012) 6598–6630, https://doi.org/10.1016/j.rser.2012.09.002.

[13] R. Offermann, T. Seidenberger, D. Thrän, M. Kaltschmitt, S. Zinoviev, S. Miertus, Assessment of global bioenergy potentials, Mitig. Adapt. Strategies Glob. Change 16 (2011) 103–115, https://doi.org/10.1007/s11027-010-9247-9.

[14] V. Dornburg, D. van Vuuren, G. van de Ven, H. Langeveld, M. Meeusen, M. Banse, M. van Oorschot, J. Ros, G. Jan van den Born, H. Aiking, M. Londo, H. Mozaffarian, P. Verweij, E. Lysen, A. Faaij, Bioenergy revisited: key factors in global potentials of bioenergy, Energy Environ. Sci. 3 (2010) 258, https://doi.org/10.1039/b922422j.

[15] A. Popp, S.K. Rose, K. Calvin, D.P. Van Vuuren, J.P. Dietrich, M. Wise, E. Stehfest, F. Humpenöder, P. Kyle, J. Van Vliet, N. Bauer, H. Lotze-Campen, D. Klein, E. Kriegler, Land-use transition for bioenergy and climate stabilization: model comparison of drivers, impacts and interactions with other land use based mitigation options, Climatic Change 123 (2014) 495–509, https://doi.org/10.1007/s10584-013-0926-x.

[16] K. Calvin, M. Wise, P. Kyle, P. Patel, L. Clarke, J. Edmonds, Trade-offs of different land and bioenergy policies on the path to achieving climate targets, Climatic Change 123 (2014) 691–704, https://doi.org/10.1007/s10584-013-0897-y.

[17] P. Smith, H. Haberl, A. Popp, K. Erb, C. Lauk, R. Harper, F.N. Tubiello, A. de Siqueira Pinto, M. Jafari, S. Sohi, O. Masera, H. Böttcher, G. Berndes, M. Bustamante, H. Ahammad, H. Clark, H. Dong, E.A. Elsiddig, C. Mbow, N. H. Ravindranath, C.W. Rice, C. Robledo Abad, A. Romanovskaya, F. Sperling, M. Herrero, J.I. House, S. Rose, How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? Global Change Biol. 19 (2013) 2285–2302, https://doi.org/10.1111/gcb.12160.

[18] A. Popp, J.P. Dietrich, H. Lotze-Campen, D. Klein, N. Bauer, M. Krause, T. Beringer, D. Gerten, O. Edenhofer, The economic potential of bioenergy for climate change mitigation with special attention given to implications for the land system, Environ. Res. Lett. 6 (2011), https://doi.org/10.1088/1748-9326/6/3/034017.

[19] J.C. Doelman, E. Stehfest, A. Tabeau, H. van Meijl, L. Lassaletta, D.E.H.J. Gernaat, K. Neumann-Hermans, M. Harmsen, V. Daioglou, H. Biemans, S. van der Sluis, D. P. van Vuuren, Exploring SSP land-use dynamics using the IMAGE model: regional and gridded scenarios of land-use change and land-based climate change mitigation, Global Environ. Change 48 (2018) 119–135, https://doi.org/10.1016/j.gloenvcha.2017.11.014.

[20] P. Smith, M. Bustamante, H. Ahammad, J. Van Minnen, Agriculture, Forestry and Other Land Use (AFOLU), in: Clim. Chang. 2014 Mitig. Clim. Chang. Contrib. Work. Gr. III to Fifth Assess. Rep. Intergov. Panel Clim. Chang, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014, pp. 811–922. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter11.pdf.

[21] A.D. Pulido, N. Chaparro, S. Granados, E. Ortiz, A. Rojas, F. Torres, J. David Turriago, M. Hernández Garzón, Informe de Inventario Nacional de GEI de Colombia, Bogotá D.C., Colombia (2019). https://unfccc.int/documents/194659.

[22] W. Vergara, A.R. Rios, L.M. Galindo, P. Gutman, P. Isbell, P.H. Suding, J. Samaniego, The Climate and Development Challenge for Latin America and the Caribbean: Options for Climate-Resilient, Low-Carbon Development, Inter-American Development Bank, New York, NY, 2013. https://publications.iadb.org/handle/11319/456.

[23] R.M. Roman-Cuesta, M.C. Rufino, M. Herold, K. Butterbach-Bahl, T.S. Rosenstock, M. Herrero, S. Ogle, C. Li, B. Poulter, L. Verchot, C. Martius, J. Stuiver, S. de Bruin, Hotspots of gross emissions from the land use sector: patterns, uncertainties, and leading emission sources for the period 2000–2005 in the tropics, Biogeosciences 13 (2016) 4253–4269, https://doi.org/10.5194/bg-13-4253-2016.

[24] C. Hong, J.A. Burney, J. Pongratz, J.E.M.S. Nabel, N.D. Mueller, R.B. Jackson, S. J. Davis, Global and regional drivers of land-use emissions in 1961–2017, Nature 589 (2021) 554–561, https://doi.org/10.1038/s41586-020-03138-y.

[25] N.L. Harris, S. Brown, S.C. Hagen, S.S. Saatchi, S. Petrova, W. Salas, M.C. Hansen, P.V. Potapov, A. Lotsch, Baseline map of carbon emissions from deforestation in tropical regions, Science (80-.) 336 (2012) 1573–1576, https://doi.org/10.1126/science.1217962.

[26] V. De Sy, M. Herold, F. Achard, R. Beuchle, J.G.P.W. Clevers, E. Lindquist, L. Verchot, Land use patterns and related carbon losses following deforestation in South America, Environ. Res. Lett. 10 (2015) 15, https://doi.org/10.1088/1748-9326/10/12/124004.

[27] V. De Sy, M. Herold, F. Achard, V. Avitabile, A. Baccini, S. Carter, J.G.P. W. Clevers, E. Lindquist, M. Pereira, L. Verchot, Tropical deforestation drivers and associated carbon emission factors derived from remote sensing data, Environ. Res. Lett. 14 (2019), https://doi.org/10.1088/1748-9326/ab3dc6.

[28] L. Mahecha, J. Angulo, Nutrient management in silvopastoral systems for economically and environmentally sustainable cattle production: a case study from Colombia, in: J. Whalen (Ed.), Soil Fertil. Improv. Integr. Nutr. Manag. - A Glob. Perspect, InTech, 2012, pp. 201–216, https://doi.org/10.5772/29476.

[29] Fedegan, Consensos ganaderos regionales, 2012 (Grupos focales), Bogotá D.C., Colombia, 2012.

[30] P.J. Gerber, H. Steinfeld, B. Henderson, A. Mottet, C. Opio, J. Dijkman, A. Falcucci, G. Tempio, Tackling Climate Change through Livestock - A Global Assessment of Emissions and Mitigation Opportunities, Food and Agriculture Organization of the United Nations, Rome, Italy, 2013. http://www.fao.org/3/i3437e/i3437e00.htm.

[31] A. Popp, K. Calvin, S. Fujimori, P. Havlik, F. Humpenöder, E. Stehfest, B. L. Bodirsky, J.P. Dietrich, J.C. Doelmann, M. Gusti, T. Hasegawa, P. Kyle, M. Obersteiner, A. Tabeau, K. Takahashi, H. Valin, S. Waldhoff, I. Weindl, M. Wise, E. Kriegler, H. Lotze-Campen, O. Fricko, K. Riahi, D.P. van Vuuren, Land-use futures in the shared socio-economic pathways, Global Environ. Change 42 (2017) 331–345, https://doi.org/10.1016/j.gloenvcha.2016.10.002.

[32] B. Wicke, F. van der Hilst, V. Daioglou, M. Banse, T. Beringer, S. Gerssen-Gondelach, S. Heijnen, D. Karssenberg, D. Laborde, M. Lippe, H. van Meijl, A. Nassar, J. Powell, A.G. Prins, S.N.K. Rose, E.M.W. Smeets, E. Stehfest, W. E. Tyner, J.A. Verstegen, H. Valin, D.P. van Vuuren, S. Yeh, A.P.C. Faaij, Model collaboration for the improved assessment of biomass supply, demand, and impacts, GCB Bioenergy 7 (2015) 422–437, https://doi.org/10.1111/gcbb.12176.

[33] M.A. Gonzalez-Salazar, M. Morini, M. Pinelli, P.R. Spina, M. Venturini, M. Finkenrath, W.-R. Poganietz, Methodology for estimating biomass energy potential and its application to Colombia, Appl, Energy 136 (2014) 781–796, https://doi.org/10.1016/j.apenergy.2014.07.004.

[34] H. Escalante Hernández, J. Orduz Prada, H.J. Zapata Lesmes, M.C. Cardona Ruiz, M. Duarte Ortega, Atlas del Potential Energético de la Biomasa Residual en Colombia. Reporte preparado para la Unidad de Planeación Minero Energética (U, Bogotá (2011), https://doi.org/10.1017/CBO9781107415324.004.
[35] M.A. Gonzalez-Salazar, M. Venturini, W.R. Poganietz, M. Finkenrath, P.R. Spina, Methodology for improving the reliability of biomass energy potential estimation, Biomass Bioenergy 88 (2016) 43–58, https://doi.org/10.1016/j.biombioe.2016.03.026.
[36] UPME, Formulación de instrumentos técnicos que estimulen el aprovechamiento de la biomasa en la generación de energía a partir de fuentes no convencionales de energía - FNCE: producto 2 Soporte técnico y jurídico para el aprovechamiento energético de la biomasa, Bogotá D.C., Colombia (2015).
[37] M.A. Gonzalez-Salazar, M. Morini, M. Pinelli, P.R. Spina, M. Venturini, M. Finkenrath, W.-R. Poganietz, Methodology for biomass energy potential estimation: projections of future potential in Colombia, Renew, Energy 69 (2014) 488–505, https://doi.org/10.1016/j.renene.2014.03.056.
[38] C.E. Jimenez Morales, Palm Oil Biodiesel in Colombia, a GIS Based Exploratory Study on its Potential and Scenarios for the Future, Master thesis, Utrecht University, 2012, https://dspace.library.uu.nl/handle/1874/252962.
[39] E. Murgueitio, R. Barahona, J.D. Chará, M.X. Flores, R.M. Mauricio, J.J. Molina, The intensive silvopastoral systems in Latin America sustainable alternative to face climatic change in animal husbandry, Cuba, J. Agric. Sci. 49 (2015) 541–554.
[40] J. Chará, E. Reyes, P. Peri, J. Otte, E. Arce, F. Schneider, Silvopastoral Systems and Their Contribution to Improved Resource Use and Sustainable Development Goals: Evidence from Latin America, FAO, CIPAV and Agri Benchmark, Cali, Colombia, 2019. http://www.cipav.org.co/pdf/SPS_Report_ISBN_FAO.pdf.
[41] Z. Calle, E. Murgueitio, J. Chará, C.H. Molina, A.F. Zuluaga, A. Calle, A strategy for scaling-up intensive silvopastoral systems in Colombia, J. Sustain. For. 32 (2013) 677–693, https://doi.org/10.1080/10549811.2013.817338.
[42] C.A. Cuartas, J.F. Naranjo, A.M. Tarazona, E. Murgueitio, J.D. Chará, J. Ku, F. J. Solorio, M.X. Flores, B. Solorio, R. Barahona, Contribution of intensive silvopastoral systems to animal performance and to adaptation and mitigation of climate change, Rev. Colombiana Ciencias Pecuarias 27 (2014) 76–94.
[43] L. Mahecha, G. Corral, M. Murgueitio, C.S. Brito, J. Angulo, M. Olivera, B. Solorio, A. Zapata, C. Cuartas, J.F. Naranjo, C. Rodríguez-Muela, J. Ramírez, A. Mejía, M.X. Flores, E. Murgueitio, Avances de investigación: SSPi producen elevada cantidad de carne de alta calidad en Colombia y México, Cart. Fedegán 129 (2012) 60–72.
[44] X. Gaviria, C.P. Sossa, C. Montoya, J. Chará, J.J. Lopera, C.P. Córdoba, R. Barahona, Producción de Carne Bovina en Sistemas Silvopastoriles Intensivos en el Trópico Bajo Colombiano, in: VII Congr. Latinoam. Sist. Agroforestales Para La Prod. Anim. Sosten, 2012, pp. 1–5. Belém, Brazil.
[45] J.F. Naranjo, C.A. Cuartas, E. Murgueitio, J. Chará, R. Barahona, Balance de gases de efecto invernadero en sistemas silvopastoriles intensivos con leucaena leucocephala en Colombia, Livest. Res. Rural Dev. 24 (2012) 8–24.
[46] Ganadería Fedegan, Colombiana: hoja de ruta 2018-2022, Federación Colombiana de Ganaderos, Bogotá D.C., Colombia (2018). http://static.fedegan.org.co.s3.amazonaws.com/publicaciones/Hoja_de_ruta_Fedegan.pdf.
[47] Nota ECDBC, De información de la NAMA Ganadería Bovina Sostenible, Bogotá D.C., Colombia (2015).
[48] N.E. Ramirez-Contreras, D. Munar-Florez, F. van der Hilst, J.C. Espinosa, A. Ocampo-Duran, J. Ruíz-Delgado, D. Molina, J.A. Garcia-Nuñez, A.P.C. Faaij, GHG balance of agricultural intensification & bioenergy production in the Orinoquia region, Colombia, Manuscript in preparation (2020).
[49] M. Haase, C. Rösch, D. Ketzer, GIS-based assessment of sustainable crop residue potentials in European regions, Biomass Bioenergy 86 (2016) 156–171, https://doi.org/10.1016/j.biombioe.2016.01.020.
[50] M. Saha, M.J. Eckelman, Geospatial assessment of regional scale bioenergy production potential on marginal and degraded land, Resour. Conserv. Recycl. 128 (2018) 90–97, https://doi.org/10.1016/j.resconrec.2017.09.008.
[51] F. Hellmann, P.H. Verburg, Spatially explicit modelling of biofuel crops in Europe, Biomass Bioenergy 35 (2011) 2411–2424, https://doi.org/10.1016/j.biombioe.2008.09.003.
[52] F. Van der Hilst, J.A. Verstegen, D. Karssenberg, A.P.C. Faaij, Spatiotemporal land use modelling to assess land availability for energy crops - illustrated for Mozambique, GCB Bioenergy 4 (2012) 859–874, https://doi.org/10.1111/j.1757-1707.2011.01147.x.
[53] F. van der Hilst, A.P.C. Faaij, Spatiotemporal cost-supply curves for bioenergy production in Mozambique, Biofuels, Bioprod, Biorefining 6 (2012) 405–430, https://doi.org/10.1002/bbb.1332.
[54] J.A. Verstegen, D. Karssenberg, F. van der Hilst, A.P.C. Faaij, Identifying a land use change cellular automaton by Bayesian data assimilation, Environ. Model. Software 53 (2014) 121–136, https://doi.org/10.1016/j.envsoft.2013.11.009.
[55] J.A. Verstegen, D. Karssenberg, F. van der Hilst, A.P.C. Faaij, Detecting systemic change in a land use system by Bayesian data assimilation, Environ. Model. Software 75 (2016) 424–438, https://doi.org/10.1016/j.envsoft.2015.02.013.
[56] J.A. Verstegen, F. van der Hilst, G. Woltjer, D. Karssenberg, S.M. de Jong, A.P. C. Faaij, What can and can't we say about indirect land-use change in Brazil using an integrated economic - land-use change model? GCB Bioenergy 8 (2016) 561–578, https://doi.org/10.1111/gcbb.12270.
[57] L. Hamelin, M. Borzęcka, M. Kozak, R. Pudełko, A spatial approach to bioeconomy: quantifying the residual biomass potential in the EU-27, Renew. Sustain, Energy Rev. 100 (2019) 127–142, https://doi.org/10.1016/j.rser.2018.10.017.
[58] L.S. Esteban, J.E. Carrasco, Biomass resources and costs: assessment in different EU countries, Biomass Bioenergy 35 (2011) S21–S30, https://doi.org/10.1016/j.biombioe.2011.03.045.
[59] G.M. Banowetz, A. Boateng, J.J. Steiner, S.M. Griffith, V. Sethi, H. El-Nashaar, Assessment of straw biomass feedstock resources in the Pacific Northwest, Biomass Bioenergy 32 (2008) 629–634, https://doi.org/10.1016/j.biombioe.2007.12.014.
[60] M. Gauder, S. Graeff-Hönninger, W. Claupein, Identifying the regional straw potential for energetic use on the basis of statistical information, Biomass Bioenergy 35 (2011) 1646–1654, https://doi.org/10.1016/j.biombioe.2010.12.041.
[61] S. Kim, B.E. Dale, Global potential bioethanol production from wasted crops and crop residues, Biomass Bioenergy 26 (2004) 361–375, https://doi.org/10.1016/j.biombioe.2003.08.002.
[62] N. Scarlat, M. Martinov, J.F. Dallemand, Assessment of the availability of agricultural crop residues in the European Union: potential and limitations for bioenergy use, Waste Manag. 30 (2010) 1889–1897, https://doi.org/10.1016/j.wasman.2010.04.016.
[63] S.Y. Searle, C.J. Malins, Waste and residue availability for advanced biofuel production in EU Member States, Biomass Bioenergy 89 (2016) 2–10, https://doi.org/10.1016/j.biombioe.2016.01.008.
[64] G. Fischer, S. Prieler, H. Van Velthuizen, S.M. Lensink, M. Londo, M. De Wit, Biofuel production potentials in Europe: sustainable use of cultivated land and pastures. Part I: land productivity potentials, Biomass Bioenergy 34 (2010) 159–172, https://doi.org/10.1016/j.biombioe.2009.07.008.
[65] G. Fischer, S. Prieler, H. van Velthuizen, G. Berndes, A. Faaij, M. Londo, M. de Wit, Biofuel production potentials in Europe: sustainable use of cultivated land and pastures, Part II: land use scenarios, Biomass Bioenergy 34 (2010) 173–187, https://doi.org/10.1016/j.biombioe.2009.07.009.
[66] M. de Wit, A. Faaij, European biomass resource potential and costs, Biomass Bioenergy 34 (2010) 188–202, https://doi.org/10.1016/j.biombioe.2009.07.011.
[67] J. van Dam, A.P.C. Faaij, I. Lewandowski, G. Fischer, Biomass production potentials in Central and Eastern Europe under different scenarios, Biomass Bioenergy 31 (2007) 345–366, https://doi.org/10.1016/j.biombioe.2006.10.001.
[68] B. Batidzirai, A.P.C. Faaij, E. Smeets, Biomass and bioenergy supply from Mozambique, Energy Sustain. Dev. 10 (2006) 54–81, https://doi.org/10.1016/S0973-0826(08)60507-4.
[69] E.M.W. Smeets, A.P.C. Faaij, The impact of sustainability criteria on the costs and potentials of bioenergy production - applied for case studies in Brazil and Ukraine, Biomass Bioenergy 34 (2010) 319–333, https://doi.org/10.1016/j.biombioe.2009.11.003.
[70] G. Fischer, H. van Velthuizen, F.O. Nachtergaele, Global agro-ecological zones assessment: methodology and results, Interim Report, Laxenburg, Austria, http://pure.iiasa.ac.at/id/eprint/6182/, 2000.
[71] V. Daioglou, E. Stehfest, B. Wicke, A. Faaij, D.P. van Vuuren, Projections of the availability and cost of residues from agriculture and forestry, GCB Bioenergy 8 (2016) 456–470, https://doi.org/10.1111/gcbb.12285.
[72] Mapa IGAC, Oficial político administrativo, Atlas Colomb (1999). https://geoportal.igac.gov.co/contenido/mapas-nacionales. (Accessed 21 May 2020).
[73] IGAC, Mapa de regiones naturales, Mapas Colomb (1997). http://www2.igac.gov.co/ninos/contenidos/mapas_escolares.jsp?idMenu=3. (Accessed 21 May 2020).
[74] Madr, Anuario Estadístico del Sector Agropecuario 2014, Ministerio de Agricultura y Desarrollo Rural, MADR, Bogotá D.C., Colombia (2016). http://hdl.handle.net/11438/8506.
[75] L. Mahecha, L.A. Gallego, F.J. Peláez, Situación actual de la ganadería de carne en Colombia y alternativas para impulsar su competitividad y sostenibilidad, ISSN-e 0120-0690, Rev. Colombiana Ciencias Pecuarias 15 (2) (2002) 213–225, 15 (2002) 213–225, https://dialnet.unirioja.es/servlet/articulo?codigo=3242901.
[76] E. Murgueitio, Z. Calle, F. Uribe, A. Calle, B. Solorio, Native trees and shrubs for the productive rehabilitation of tropical cattle ranching lands, For. Ecol. Manage 261 (2011) 1654–1663, https://doi.org/10.1016/j.foreco.2010.09.027.
[77] Fao, Food balance sheets. http://www.fao.org/faostat/en/#data/FBS/report, 2016. (Accessed 7 December 2018).
[78] N. Alexandratos, J. Bruinsma, World Agriculture towards 2030/2050: the 2012 Revision, 2012, https://doi.org/10.1016/S0264-8377(03)00047-4. Rome, Italy.
[79] Global Fao, Food Losses and Food Waste - Extent, Causes and Prevention, Food and Agriculture Organization of the United Nations, Rome, Italy, 2011, https://doi.org/10.1098/rstb.2010.0126.
[80] Profor, Análisis de las, Cadenas de valor y de la logística de plantaciones forestales con fines comerciales en Colombia, Bogotá, Colombia (2017).
[81] Profor, Situación actual y potencial de fomento de plantaciones forestales con fines comerciales en Colombia, Bogotá, Colombia (2017).
[82] World Bank, Population, total - Colombia, united nations popul. Div. World popul. Prospect. 2019 revis. https://data.worldbank.org/indicator/SP.POP.TOTL?locations=CO&view=chart, 2019. (Accessed 26 August 2019).
[83] K. Riahi, D.P. van Vuuren, E. Kriegler, J. Edmonds, B.C. O'Neill, S. Fujimori, N. Bauer, K. Calvin, R. Dellink, O. Fricko, W. Lutz, A. Popp, J.C. Cuaresma, S. Kc, M. Leimbach, L. Jiang, T. Kram, S. Rao, J. Emmerling, K. Ebi, T. Hasegawa, P. Havlik, F. Humpenöder, L.A. Da Silva, S. Smith, E. Stehfest, V. Bosetti, J. Eom, D. Gernaat, T. Masui, J. Rogelj, J. Strefler, L. Drouet, V. Krey, G. Luderer, M. Harmsen, K. Takahashi, L. Baumstark, J.C. Doelman, M. Kainuma, Z. Klimont, G. Marangoni, H. Lotze-Campen, M. Obersteiner, A. Tabeau, M. Tavoni, The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview, Global Environ. Change 42 (2017) 153–168, https://doi.org/10.1016/j.gloenvcha.2016.05.009.

[84] S.K.C.W. Lutz, The human core of the shared socioeconomic pathways: population scenarios by age, sex and level of education for all countries to 2100, Global Environ. Change 42 (2017) 181–192, https://doi.org/10.1016/j.gloenvcha.2014.06.004.
[85] DANE, Proyecciones nacionales y departmentales de población 2005-2020, Bogotá D.C., Colombia (2009). https://www.dane.gov.co/files/investigaciones/poblacion/proyepobla06_20/7Proyecciones_poblacion.pdf.
[86] H.A. Delgado Rodriguez, Farm Animal Welfare in Colombia: a country situation report, Bogotá D.C., Colombia (2007). https://www.worldanimalprotection.ca/sites/default/files/media/ca_-_en_files/farmanimalwelfareincolombia_tcm22-8296.pdf.
[87] Fedegan, Producción - tasa de extracción, Estadísticas, n.d. https://www.fedegan.org.co/estadisticas/produccion-0. (Accessed 30 May 2019).
[88] Fedegan, Inventário ganadero, estadísticas, n.d. https://www.fedegan.org.co/estadisticas/inventario-ganadero. (Accessed 21 August 2020).
[89] J. Viloria de la Hoz, Documentos de Trabajo sobre Economia Regional: La ganadería bovina en las llanuras del Caribe colombiano, Cartagena, Colombia (2003). https://www.banrep.gov.co/sites/default/files/publicaciones/archivos/DTSER-40.pdf.
[90] DANE, Encuesta nacional agropecuaria (ENA) 2013, Encuesta Nac. Agropecu. Históricos (2014). https://www.dane.gov.co/index.php/estadisticas-por-tema/agropecuario/encuesta-nacional-agropecuaria-ena/encuesta-nacional-agropecuaria-por-departamentos. (Accessed 21 August 2020).
[91] DANE, Censo Nacional Agropecuario 2014: entrega de Resultados del 3er Censo Nacional Agropecuario (Definitiva). Anexo 1. https://www.dane.gov.co/index.php/estadisticas-por-tema/agropecuario/censo-nacional-agropecuario-2014#1, 2014. (Accessed 5 June 2020).
[92] Fedegan, Fichas de caracterización departamental, Fed. Colomb. Ganad (2015). https://www.fedegan.org.co/estadisticas/documentos-de-estadistica. (Accessed 19 May 2019).
[93] C.A. Díaz, M.N. Rodríguez, V.J. Vera, G. Ramírez, G.A. Casas, J.D. Mogollón, Caracterización de los sistemas de producción porcina en las principales regiones porcicolas colombianas, Rev. Colombiana Ciencias Pecuarias 24 (2011) 131–144. http://www.redalyc.org/articulo.oa?id=295022381005.
[94] M.M. Mekonnen, A.Y. Hoekstra, A global assessment of the water footprint of farm animal products, Ecosystems 15 (2012) 401–415, https://doi.org/10.1007/s10021-011-9517-8.
[95] P. O'Brien, J. Kruse, J. Link, Outlook Colombia 2030: a groundbreaking strategic analysis of the Colombian feed & livestock sector and implications for U.S. Feed grains exports, Washington DC, USA, https://silo.tips/queue/outlook-colombia-a-groundbreaking-strategic-analysis-of-the-colombian-feed-lives?&queue_id=-1&v=1597916801&u=ODcuMjE0LjEzOS4yNA==, 2016.
[96] DANE, Encuesta de Sacrificio de Ganado (ESAG), 2014. Bogotá D.C., Colombia.
[97] DANE, Cuenta Satélite Piloto de la Agroindustria (CSPA): Cría de aves de corral y su primer nivel de transformación industrial - Resultados preliminares, 2015, pp. 2005–2014. Bogotá D.C., Colombia.
[98] C. Campabadal, Guía Técnica para Alimentación de Cerdos, 2009. San José, Costa Rica, http://www.mag.go.cr/bibliotecavirtual/a00144.pdf.
[99] DANE, Alimentos completos balanceados en la nutrición de las aves de corral - Boletín mensual Insumos y factores asociados a la producción agropecuaria, 2013. Bogotá D.C., Colombia, https://www.dane.gov.co/files/investigaciones/agropecuario/sipsa/insumos_factores_de_produccion_enero_2013.pdf.
[100] UPRA, Zonificación de aptitud para los cultivos maíz, palma de aceite y plantaciones comerciales en Colombia, 2019 a escala 1:100.000, https://sipra.upra.gov.co/. (Accessed 23 May 2019).
[101] CUE, Capitulo III: estudio SIG - potential de Expansión, in: C.U.E. Consorcio (Ed.), Evaluación Del Ciclo Vida La Cadena Prod. Biocombustibles En Colomb. Proy. "Estrategias Energía Sosten. Y Biocombustibles Para Colomb. ATN/JC-10826-CO Y ATN/JF-10827-CO", Medellín, 2012, p. 130.
[102] DANE, Cuenta satélite piloto de la agroindustria de la palma de aceite: palma en desarrollo, en producción y su primer nivel de transformación 2005-2010, Bogotá D.C., Colombia (2012), 1. Departamento Administrativo Nacional de Estadística (DANE) [Internet]. [cited 2015 Mar 5]. Available from, http://www.dane.gov.co/index.php/poblacion-y-demografia/censos.
[103] DANE, Cuenta satélite piloto de la agroindustria del cultivo de caña de azúcar 2005-2012, Bogotá D.C., Colombia (2012) oi:1. Departamento Administrativo Nacional de Estadística (DANE) [Internet]. [cited 2015 Mar 5]. Available from, http://www.dane.gov.co/index.php/poblacion-y-demografia/censos.
[104] J.A. Garcia-Nunez, D.T. Rodriguez, C.A. Fontanilla, N.E. Ramirez, E.E. Silva Lora, C.S. Frear, C. Stockle, J. Amonette, M. Garcia-Perez, Evaluation of alternatives for the evolution of palm oil mills into biorefineries, Biomass Bioenergy 95 (2016) 310–329, https://doi.org/10.1016/j.biombioe.2016.05.020.
[105] TNO, Phyllis2 database for biomass and waste. https://phyllis.nl/Browse/Standard/ECN-Phyllis, 2020. (Accessed 25 June 2020).
[106] T. Lap, R. Benders, A. Köberle, F. van der Hilst, L. Nogueira, A. Szklo, R. Schaeffer, A. Faaij, Pathways for a Brazilian biobased economy: towards optimal utilization of biomass, Biofuels, Bioprod. Biorefining 13 (2019) 673–689, https://doi.org/10.1002/bbb.1978.
[107] M. Mosquera Montoya, M. Valderrama Villabona, E. Ruíz Álvarez, D. López Alfonso, L. Enrique Castro Zamudio, C. Andrés Fontanilla, M. Alejandra González Arenas, Economic production costs for the fruit of oil palms and crude palm oil in 2016: estimation in a group of Colombian producers. http://web.fedepalma.org/media/01-Palmas-38-2-2017_VF_sin_marcas.pdf, 2017.
[108] M. Mosquera-Montoya, E. Ruiz-Alvarez, E. Mesa-Fuquen, Economic assessment of technology adoption in oil palm plantations from Colombia, Int. J. Financ. Res. 8 (2017) 74, https://doi.org/10.5430/ijfr.v8n3p74.
[109] IMR, Subnational Human Development Index (2.2). Institute for Management Research, Radboud University., 2019. https://globaldatalab.org/shdi/shdi/. (Accessed 25 February 2019).
[110] DANE, Madr, El arroz: producción en Colombia. SIPSA. Boletín mensual INSUMOS Y FACTORES ASOCIADOS A LA PRODUCCIÓN AGROPECUARIA, Boletin 12 (2013) 1–7.
[111] J. Cassalett Dávila, Clímaco Torres Aguas, E. Camilo Isaacs, El cultivo de la caña en la zona azucarera de Colombia, 1995. Cali, Colombia.
[112] C. Augusto Borrero, Cultivo de la Palma de Aceite (parte IV), n.d. https://www.infoagro.com/documentos/cultivo_palma_aceite__parte_iv_.asp. (Accessed 23 January 2020).
[113] A.N. Motato, R.J. Barba, Manual de nutrición y fertilización de la palma africana, Ecuador, Santo Domingo, 1990.
[114] C.M. Ospina Penagos, R.J. Hernández Restrepo, C.A. Rodas, J.B. Urrego Mesa, J. Godoy, F. Aristizábal, O. Osorio, N. Riaño, El Eucalipto (Eucalyptus Grandis W. Hill Ex Maiden), Cenicafe, Bogotá D.C., Colombia, 2006.
[115] R. Guerrero Riascos, Fertilización de cultivos en clima medio, Monómeros Colombo Venezolanos S.A. (E.M.A.), 1995. Bogotá D.C., Colombia.
[116] J. Gao, A. Zhang, S.K. Lam, X. Zhang, A.M. Thomson, E. Lin, K. Jiang, L.E. Clarke, J.A. Edmonds, P.G. Kyle, S. Yu, Y. Zhou, S. Zhou, An integrated assessment of the potential of agricultural and forestry residues for energy production in China, GCB Bioenergy 8 (2016) 880–893, https://doi.org/10.1111/gcbb.12305.
[117] A. Koopmans, J. Koppejan, Agricultural and forest residues - generation, utilization and availability, in: Reg. Consult. Mod. Appl. Biomass Bioenergy, 1997, pp. 1–23, 6-10 January 1997, Kuala Lampur, Malaysia, Kuala Lampur, Malaysia.
[118] K. Rodríguez Cáceres, F.G. Blanco Patiño, J.A. Araque Duarte, V. Kafarov, Assessment of the energy potential of agricultural residues in non-interconnected zones of Colombia: case study of Chocó and Putumayo, Chem. Eng. Trans. 50 (2016) 349–354, https://doi.org/10.3303/CET1650059.
[119] B. Boundy, S.W. Diegel, L. Wright, S.C. Davis, Biomass Energy Databook: Edition 4-ORNL/TM-2011/446, cta.ornl.gov/bedb, 2011. Oak Ridge, TN, United States of America.
[120] S. Zafar, How is biomass transported. https://www.bioenergyconsult.com/biomass-transportation/, 2020. (Accessed 31 August 2020).
[121] R. Swart, P. Raskin, J. Robinson, The problem of the future: sustainability science and scenario analysis, Glob, Environ. Change 14 (2004) 137–146, https://doi.org/10.1016/j.gloenvcha.2003.10.002.
[122] B.C. O'Neill, E. Kriegler, K. Riahi, K.L. Ebi, S. Hallegatte, T.R. Carter, R. Mathur, D.P. van Vuuren, A new scenario framework for climate change research: the concept of shared socioeconomic pathways, Clim, Change 122 (2014) 387–400, https://doi.org/10.1007/s10584-013-0905-2.
[123] Fao, The future of food and agriculture - alternative pathways to 2050, Rome, 2018, p. 224, https://doi.org/10.4161/chan.4.6.12871. Licence: CC BY-NC-SA 3.0 IGO.
[124] World Bank, GDP, PPP (Constant 2011 International $) - Colombia, World Bank, Int, 2019. Comp. Progr. Database, https://data.worldbank.org/indicator/NY.GDP.MKTP.PP.KD?locations=CO&view=chart. (Accessed 26 August 2019).
[125] RIVM, NEVO online 2019: Dutch food composition database 2019. https://www.rivm.nl/en/dutch-food-composition-database/access-nevo-data/nevo-online, 2019 accessed January 21, 2020.
[126] P.W. Gerbens-Leenes, S. Nonhebel, M.S. Krol, Food consumption patterns and economic growth. Increasing affluence and the use of natural resources, Appetite 55 (2010) 597–608, https://doi.org/10.1016/j.appet.2010.09.013.
[127] Microsoft, FORECAST.ETS function, Forecast. Funct, n.d. https://support.office.com/en-us/article/forecast-ets-function-15389b8b-677e-4fbd-bd95-21d464333f41. (Accessed 30 May 2019).
[128] Fedegan, Mercado de la Carne: coyuntura y perspectativas, Bogotá D.C., Colombia, https://www.fedegan.org.co/publicacion-presentaciones/mercado-de-la-carne-coyuntura-y-perspectivas, 2015.
[129] E. Smeets, M. van Leeuwen (Eds.), Annotated Bibliography on Qualitative and Quantitative Models for Analysing the Bio-Based Economy, 2014. The Hague, Netherlands.
[130] R.S. Dodder, A. Elobeid, T.L. Johnson, P.O. Kaplan, L.A. Kurkalova, S. Secchi, S. Tokgoz, Environmental impacts of emerging biomass feedstock markets: energy, agriculture, and the farmer. http://www.card.iastate.edu/publications/dbs/pdffiles/11wp526.pdf, 2011.
[131] J. Popp, Z. Lakner, M. Harangi-Rákos, M. Fári, The effect of bioenergy expansion: food, energy, and environment, Renew. Sustain, Energy Rev. 32 (2014) 559–578, https://doi.org/10.1016/j.rser.2014.01.056.
[132] V. Daioglou, M. Muratori, P. Lamers, S. Fujimori, A. Kitous, A.C. Köberle, N. Bauer, M. Junginger, E. Kato, F. Leblanc, S. Mima, M. Wise, D.P. van Vuuren, Implications of climate change mitigation strategies on international bioenergy trade, Climatic Change 163 (2020) 1639–1658, https://doi.org/10.1007/s10584-020-02877-1.
[133] F. Creutzig, N.H. Ravindranath, G. Berndes, S. Bolwig, R. Bright, F. Cherubini, H. Chum, E. Corbera, M. Delucchi, A. Faaij, J. Fargione, H. Haberl, G. Heath, O. Lucon, R. Plevin, A. Popp, C. Robledo-Abad, S. Rose, P. Smith, A. Stromman, S. Suh, O. Masera, Bioenergy and climate change mitigation: an assessment, GCB Bioenergy 7 (2015) 916–944, https://doi.org/10.1111/gcbb.12205.
[134] S. Frank, M. Gusti, P. Havlík, P. Lauri, F. DiFulvio, N. Forsell, T. Hasegawa, T. Krisztin, A. Palazzo, H. Valin, Land-based climate change mitigation potentials within the agenda for sustainable development, Environ. Res. Lett. 16 (2021), https://doi.org/10.1088/1748-9326/abc58a.
[135] P. Alexander, M.D.A. Rounsevell, C. Dislich, J.R. Dodson, K. Engström, D. Moran, Drivers for global agricultural land use change: the nexus of diet, population,

yield and bioenergy, Glob. Environ, Chang. Times 35 (2015) 138–147, https://doi.org/10.1016/j.gloenvcha.2015.08.011.
[136] T. Kastner, M.J.I. Rivas, W. Koch, S. Nonhebel, Global changes in diets and the consequences for land requirements for food, Proc. Natl. Acad. Sci. Unit. States Am. 109 (2012) 6868–6872, https://doi.org/10.1073/pnas.1117054109.
[137] E.V. Elferink, S. Nonhebel, Variations in land requirements for meat production, J. Clean. Prod. 15 (2007) 1778–1786, https://doi.org/10.1016/j.jclepro.2006.04.003.
[138] E. Stehfest, L. Bouwman, D.P. Van Vuuren, M.G.J. Den Elzen, B. Eickhout, P. Kabat, Climate benefits of changing diet, Climatic Change 95 (2009) 83–102, https://doi.org/10.1007/s10584-008-9534-6.
[139] R.D. Semba, S. de Pee, B. Kim, S. McKenzie, K. Nachman, M.W. Bloem, Adoption of the 'planetary health diet' has different impacts on countries' greenhouse gas emissions, Nat. Food 1 (2020) 481–484, https://doi.org/10.1038/s43016-020-0128-4.
[140] B.F. Kim, R.E. Santo, A.P. Scatterday, J.P. Fry, C.M. Synk, S.R. Cebron, M. M. Mekonnen, A.Y. Hoekstra, S. de Pee, M.W. Bloem, R.A. Neff, K.E. Nachman, Country-specific dietary shifts to mitigate climate and water crises, Global Environ. Change 62 (2020) 101926, https://doi.org/10.1016/j.gloenvcha.2019.05.010.
[141] F. Pendrill, U.M. Persson, J. Godar, T. Kastner, D. Moran, S. Schmidt, R. Wood, Agricultural and forestry trade drives large share of tropical deforestation emissions, Global Environ. Change 56 (2019) 1–10, https://doi.org/10.1016/j.gloenvcha.2019.03.002.
[142] N.D. Mueller, J.S. Gerber, M. Johnston, D.K. Ray, N. Ramankutty, J.A. Foley, Closing yield gaps through nutrient and water management, Nature 490 (2012) 254–257, https://doi.org/10.1038/nature11420.
[143] M. Ibarrola-Rivas, S. Nonhebel, Variations in the use of resources for food: land, nitrogen fertilizer and food nexus, Sustainability 8 (2016) 1322, https://doi.org/10.3390/su8121322.
[144] N.D. Mueller, P.C. West, J.S. Gerber, G.K. MacDonald, S. Polasky, J.A. Foley, A tradeoff frontier for global nitrogen use and cereal production, Environ. Res. Lett. 9 (2014), https://doi.org/10.1088/1748-9326/9/5/054002.
[145] A. Popp, H. Lotze-Campen, M. Leimbach, B. Knopf, T. Beringer, N. Bauer, B. Bodirsky, On sustainability of bioenergy production: integrating co-emissions from agricultural intensification, Biomass Bioenergy 35 (2011) 4770–4780, https://doi.org/10.1016/j.biombioe.2010.06.014.
[146] C. Giraldo, F. Escobar, J.D. Chará, Z. Calle, The adoption of silvopastoral systems promotes the recovery of ecological processes regulated by dung beetles in the Colombian Andes, Insect Conserv, Divers 4 (2011) 115–122, https://doi.org/10.1111/j.1752-4598.2010.00112.x.
[147] J. Whitaker, J.L. Field, C.J. Bernacchi, C.E.P. Cerri, R. Ceulemans, C.A. Davies, E. H. DeLucia, I.S. Donnison, J.P. McCalmont, K. Paustian, R.L. Rowe, P. Smith, P. Thornley, N.P. McNamara, Consensus, uncertainties and challenges for perennial bioenergy crops and land use, GCB Bioenergy 10 (2018) 150–164, https://doi.org/10.1111/gcbb.12488.
[148] N. Canales, J. Gómez González, Policy dialogue on a bioeconomy for sustainable development in Colombia: SEI Report, Bogotá, Colombia (2020). https://www.sei.org/publications/policy-dialogue-bioeconomy-sustainable-development-colombia/.
[149] M. Meehan, K.K. Sedivec, J. Printz, F. Brummer, Determining carrying capacity and stocking rates for range and pasture in North Dakota, Fargo, ND, https://www.ag.ndsu.edu/publications/livestock/determining-carrying-capacity-and-stocking-rates-for-range-and-pasture-in-north-dakota, 2018.
[150] Madr, Resolución 261 de 2018. Por medio de la cual se define la Frontera Agrícola Nacional y se adopta la metodología para la identificación general, Bogotá D.C., Colombia (2018). https://www.minagricultura.gov.co/Normatividad/Resoluciones/Resolución.No.000261.de.2018.pdf.
[151] UPRA, Evaluación De Tierras Para La Zonificación con Fines Agropecuarios a Nivel Nacional Metodología a Escala General(1:100000), Bogotá D.C., Colombia (2013), https://doi.org/10.1017/CBO9781107415324.004.
[152] UPRA, Metodología para la identificación general de la frontera agrícola en Colombia, Bogotá D.C., Colombia (2018). http://bibliotecadigital.agronet.gov.co/handle/11438/8632.
[153] M.-J. Ibarrola-Rivas, S. Nonhebel, Does Mexico have enough land to fulfill future needs for the consumption of animal products? Agriculture 9 (2019) 211, https://doi.org/10.3390/agriculture9100211.