Carbon sequestration potential from large-scale reforestation and sugarcane expansion on abandoned agricultural lands in Brazil

Ivan Garcia Kerdan[a,*], Sara Giarola[b], Francisca Jalil-Vega[a], Adam Hawkes[a]

[a] Department of Chemical Engineering, Imperial College London, United Kingdom

[b] Earth Science & Engineering Department, Imperial College London, United Kingdom

Abstract

Since 1850, over 145 ± 16 PgC (μ ± 1σ) has been emitted worldwide due to land-use change and deforestation. Besides industrial carbon capture and storage (CCS), storing carbon in forestry products and in regenerated forest has been recognised as a cost-effective carbon sequestration option, with an estimated worldwide sink potential of about 50-100 PgC (15-36 PgC from tropical forest alone). This paper proposes the expansion of a Brazilian integrated assessment model (MUSE-Brazil) by integrating a non-spatial biomass-growth model. The aim is to account for carbon sequestration potential from either reforestation or sugarcane expansion in abandoned agricultural lands. Modelling outputs suggest that Brazil has the potential to liberate up to 32.3 Mha of agricultural land by 2035, reaching 68.4 Mha by mid-century. If a sugarcane expansion policy is promoted, by 2050, the largest sequestration rates would come from above and below ground biomass pools; gradually releasing to the atmosphere around 1.6 PgC or 1.2% of the current Brazilian land carbon stock due to lower SOC carbon pools when turning agricultural lands into sugarcane crops. On the other hand, a reforestation-only scenario projects that by 2035 the baseline year carbon stock could be recovered and by 2050 the country's carbon stock would have been increased by 3.2 PgC, reaching annual net sequestration rates of 0.1 PgC y^{-1}, mainly supported by natural vegetation regeneration in the Cerrado biome.

Keywords

land use; energy systems model; sugarcane; reforestation; carbon sequestration; Brazil

1. Introduction

At the COP21 meeting, 195 nations have consented to restrict climate change to well underneath 2°C (UN 2015). Agriculture, forestry and land use (AFOLU) is responsible of around 24% of global anthropogenic emissions (IPCC 2014). The sector is essential in accomplishing reduction targets by reducing CH_4 and N_2O emissions from farming, and decreasing CO_2 emissions from deforestation (De Oliveira Silva et al. 2018; Hasegawa and Matsuoka 2010; Scherer et al. 2018).

* Corresponding author

Email address: i.garcia-kerdan@imperial.ac.uk (Ivan Garcia Kerdan)

ORCID: https://orcid.org/0000-0002-0566-555X

Research with respect to diverse carbon sequestration processes in the AFOLU sector and in negative emissions technologies to offset the insufficient reduction in carbon emissions by the energy sector has been growing in the last decade (Minx et al. 2017). Bioenergy crops, either for biofuels production or for electricity generation, have the capacity of decreasing emissions by substituting fossil fuels. Recent research has calculated that the maximum global bioenergy supply potential stands just below 1,300 EJ y^{-1} (Haberl et al. 2010; Raphael Slade et al. 2011; Smeets et al. 2007); however, if technical and economic constraints are considered, this value decreases to around 130-400 EJ y^{-1} (Deng et al. 2015). Nijsen et al. (2012) calculated a potential at around 150-190 EJ y^{-1}, mainly coming from woody crops and grass from marginal land.

Still, several uncertainties exists, especially those related to the full bioenergy production life cycle emissions (Plevin et al. 2010). Regardless, biomass production is seen as an essential energy source to achieve climate change targets, as most mitigation pathways consider the wide implementation of biomass combined with carbon capture and storage processes (BECCS) (Azar et al. 2010). BECCS has been found to possess the best abatement potential within the power and industrial sectors with three main CCS technologies: i) pre-combustion, ii) post-combustion and iii) oxy-combustion, and with a variety of separation technologies (absorption, adsorption, membrane, etc.). However, the ecosystems and social implications of large-scale bioenergy production as well as the high capital costs of CCS technologies still need to be carefully assessed (Muratori et al. 2016). On the other hand, land management techniques such as biochar, soil carbon sequestration (SCS) and reforestation/afforestation could support carbon mitigation actions at low-cost (Minx et al. 2017). Recent studies have shown carbon benefits of restoring abandoned lands to their original state (Evans et al. 2015; Silver et al. 2000); however, similar to BECCS, there is high uncertainty in its large-scale implementation.

For Smith et al. (2013) and Yue et al. (2017), reducing meat-based diets could have larger carbon abatement potentials, mainly arising from a reduction in land and agrochemicals demand. Nevertheless, future food demand projections (FAO 2017) and lack of sustainable bioenergy policies, would put severe pressure on the land system. In some countries, the degradation of natural forest for agricultural production still remains, causing a severe environmental damage. Optimal land use management and new technologies would be necessary to increase production, minimising the demand for new lands, allowing abandoned agricultural lands to recover their natural vegetation (FAO 2017; IPCC 2014).

Silver et al. (2000) studied the carbon sequestration potential by reforestation of tropical lands. The authors identified the importance of previous agricultural land use on carbon (C) sequestration rates of biomass and soils. For instance, forests growing in previous cropland have the capacity to accumulate faster quantities of biomass due to high relative fertility, while soil organic carbon accumulates faster in former pasture lands. Krause et al. (2017) studied the carbon removal through growth of bioenergy crops via CCS and afforestation, aiming to find an optimal share to assess trade-offs of different ecosystem parameters such as surface albedo, nitrogen loss, and carbon storage. Nonetheless, reforestation strategies also have their disadvantages. One of the main limitations of forest management is the rate of decomposition that eventually releases CO_2. Some authors have suggested that more appropriate forest management techniques considering sustainable wood harvest, production of wood materials and wood storage combined with BECCS could provide a more sustainable solution. Ni et al. (2016) suggested that active harvesting strategies at a constant rate without affecting the new forest albedo are necessary

and could achieve greater GHG abatement potential. The main advantage of this approach compared to industrial CCS is its lower capital and operational cost (\$25-50 against \$100-\$160 $tonCO_2^{-1}$).

AFOLU GHG abatement models

Energy and 'agricultural & land use' models are set to play a significant role in supporting policy and decision makers in climate change mitigation policies. This is particularly relevant for this sector, which would appear having a crucial role in mitigation potential, but is at the same time characterized by large uncertainties.

Kraxner et al. (2003) developed MOSES, a forest (single tree) growth model capable to analyse forest-biomass energy systems dynamics in temperate regions. The authors demonstrated that forestry management and bioenergy growth in temperate forests could lead to the stabilisation and absorption of CO_2 emissions from the atmosphere, focusing on the advantages of BECCS as a measure to achieve negative emissions. The authors showed that reforestation and BECCS have the global potential to permanently remove 2.5 ton C yr^{-1} ha^{-1}. Contrarily, Evans et al. (2015) compared the mitigation potentials of a wide range of scenarios regarding reforestation and biofuel production on marginal or abandoned land over a 30 year period. To calculate C sequestration potential of recovered forest, a statistical analysis of temperate and tropical forests was used. The authors showed that reforestation has a larger abatement potential compared to low yielding biofuel production. Compared to gasoline production, switch grass ethanol has the largest offset emission potential (126% reduction), followed by sugarcane ethanol (96%), Miscanthus ethanol (95%), and corn ethanol (70%). Compared to diesel production, oil palm biodiesel has a reduction potential of about 65%. Nevertheless, ethanol production combined with CCS has the capability to deliver negative emissions to the energy system and could become economically competitive in the near future, as to date, the main barrier for its large-scale implementation is the large cost of capturing and transporting CO_2. Moreira et al. (2016) presented the analysis of BECCS applied to an ethanol fermentation process (considering also the production of bioelectricity). The authors found that the process would increase ethanol price by around 3.5%, with potential of governmental subsidies aiming at reducing final consumer price. Recently, Freitas et al. (2019) presented a techno-economic and thermodynamic analysis of a sugarcane-based ethanol bio-refinery demonstrating its potential to generate negative emissions. Economic viability has been increased by using the captured CO2 for enhanced oil recovery (EOR).

Albanito et al. (2016) assessed the potential implication of land use change from current cropland to either bioenergy or forest. The study developed a spatially explicit framework using several models: the spatial production allocation model (SPAM), LPJmL-DGVM, and the IPCC Tier 1 method. As a case study, the authors compared C4 grass (miscanthus and switch-grass), wood energy crops and reforestation. Globally, the authors estimated that around 420 Mha of the current 1,100 Mha of cropland, if converted to either forest or bioenergy will result in a net carbon loss. On the other hand, planting either miscanthus and/or switch-grass represents the highest abatement potential in 485 Mha, with a carbon uptake of 58 PgC. Most of these lands will be terrain with slopes above 20%. Wood-based energy crops, such as Eucalyptus, poplar and willow, are only the best option in 26.3 Mha of current cropland with an abatement potential of 0.9 Pg. Finally, reforestation provides the best option on 185 Mha with an abatement potential of 5.8 PgC from biomass and 2.7 PgC from soil carbon.

Dwivedi et al. (2016) developed a carbon forest model aiming at determining the efficiency of bioenergy and carbon markets in GHG abatement of reforested lands. Two scenarios were explored: a carbon market that could lead to an increase in forest rotation rates, and a wood-based bioenergy market that could lead to short rotation ages by selling small-diameter wood products. Findings suggest that increasing rotation times doesn't necessarily increase carbon stocks compared to normal rotations. In some regions, such as the UK, transforming all wood products into wood pellets for electricity generation leads to carbon saving offsetting emissions from fossil-fuel based plants. However, appropriate policies should be put in place to maximise the carbon saving potential of forests without any impact to the ecosystem.

To the best of the authors' knowledge, there is a lack integrated assessment models (IAMs) that combine appropriate agricultural energy technology diffusion (mechanisation) with robust land use dynamics and the implications of energy and ecosystem measures in GHG abatement. The aim of this study is to develop a framework capable of modelling mechanisation adoption, and land clearing, as well as modelling reforestation as a carbon negative measure and its wider implications in the energy and land use systems. To achieve this, MUSE-Brazil, a multi-sectoral/multi-regional energy system model has been expanded to account for land use and terrestrial emissions. The study framework is proposed in two stages. First, the model is used to simulate future energy demand and agricultural mechanisation diffusion and its implications in land use and land clearing under a reference scenario. Secondly, the model is applied to study the carbon capture and sequestration potential through either i) bioenergy growth (mainly sugarcane production) or ii) reforestation, in abandoned agricultural lands with a focus on understanding their impacts on terrestrial emissions.

The paper is organized as follows. First, an overview of the methodology and the modelling framework is presented. Secondly, the case study of Brazil's land, reforestation and bioenergy context is discussed. Then, the paper shows the obtained results, followed by discussions and conclusions.

2. Methodology

MUSE-Brazil, is a technology-rich bottom-up regional model that simulates energy, land use demand and carbon emissions in the medium and long-term (up to 2100) (García Kerdan et al. 2019) (Fig. 1). The model follows a simulation approach aiming to model real-world investors' decision making in each sector, where different methods and metrics can be implemented (e.g. ranging from merit-order simulation methods to agent-based modelling). Particularly, the model's agricultural and land use module (Ag&LU) aims to provide the required technological share and related energy consumption and emissions by meeting four general agricultural services: a) agricultural crops, b) animal-based products, c) wood products and d) energy crops. At each iteration, the Ag&LU model will dynamically exchange a set of parameters (fuel, emissions, etc.) with the Market Clearing Algorithm (MCA). The MCA connects all the different energy modules and is responsible for the data flow between sectors. Generally, the MCA will iterates between modules until each energy commodity's price and quantity converge (Crow et al. 2018). The model's simulation framework is shown in Fig. 1.
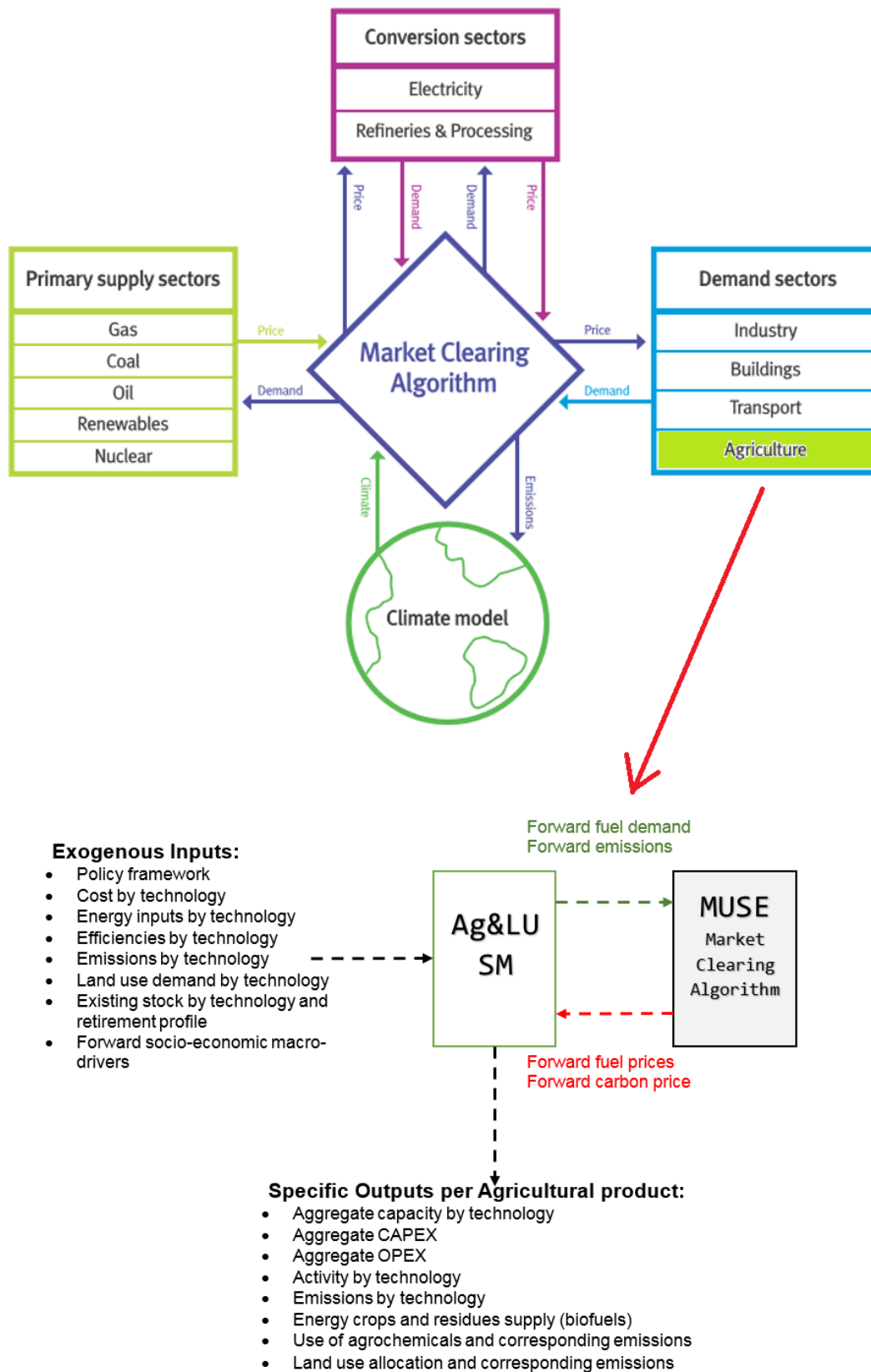
Fig. 1 MUSE-Brazil modelling framework (top) and the Ag&LU module integration into MUSE

(Data flow with the MCA) (bottom)

In this paper, MUSE-Brazil's Ag&LU module has been expanded to simulate land use requirements and related emissions. Inherited in the model is a process of simulating mechanisation uptake at each agricultural commodity while also accounting for growing demands due to increase income and total population. The new additions make the model capable of relating technological or mechanisation diffusion while predicting its impact on land use and land use clearing. Additionally, it can simulate deforestation and reforestation rates under different policies, providing a deeper understanding on the impacts of land use on carbon emissions. The model calculates available land liberated from previous agricultural land (cropland, pasture land, bioenergy land) and depending on the demand of agricultural commodities, it simulates land competition based on project's profitability. It can be constrained to limit land use expansion depending on explicit regional characteristics or environmental policies.

2.1 Land use and land use change emissions

In Ag&LU-SM, eight different land types are modelled (Table 1):

Table 1 Land types simulated in Ag&LU-SM

Type		Description
1.	*Cropland*	Land for diverse crop cultivation
2.	*Pasture land*	Land for grazing livestock
3.	*Forestry products*	Land for silviculture (wood production)
4.	*Energy crops*	Land for dedicated energy crops
5.	*Natural forest*	Land for primary and regenerated forest
6.	*Non-arable land*	Land unsuitable for farming (e.g. desert, ice, tundra, rock)
7.	*Urban/Infrastructure*	Land dedicated to human settlements and other non-natural infrastructure
8.	*Available*	Land cleared due to agricultural intensification

To account for emissions deriving from the management of land, the model integrates the IPCC Tier 1 calculation methodology (IPCC 2006). This non-spatial method provides net emissions changes for diverse land use categories over a predefined period considering the following carbon pools: above and below ground biomass, soil organic carbon (SOC) and dead organic matter (DOM). To calculate carbon stock changes at two points of time, the stock-difference method has been used:

$$\Delta C_l = \frac{(C_{l,t2} - C_{l,t1})}{(t_2 - t_1)} \tag{1}$$

where ΔC_l is the change between periods in carbon stocks in the pool l, $C_{l,t1}$ is the carbon stock at time 1 and $C_{l,t2}$ is the carbon stock at time 2. To account for changes in the carbon stock for each land type, eq. 2 is used:

$$\Delta C_{LU_i} = \Delta C_{AB} + \Delta C_{BB} + \Delta C_{DOM} + \Delta C_{SOC} \tag{2}$$

where ΔC_{LU_i} is carbon change for land use type I in the four carbon pools (above ground biomass, below ground biomass, dead organic matter and soil organic carbon). Finally, eq. 3 is used to account for the entire carbon stock changes per land-use type:

$$\Delta C_{tot} = \sum_i \Delta C_{LU_i}$$

(3)

where ΔC_{tot} is total carbon stock change. Land changes between types are also considered, as carbon dynamics vary depending on the former and latter land use type (e.g. cropland to forest, pasture to forest). These values, obtained from Guo and Gifford (2002) can be found in the Appendix (Table 8). The method has been proposed to estimate with better accuracy carbon sequestration/release from either forest recovery or new agricultural crops.

2.2   Case study

In this paper, Brazil is used as a case study. The original model (MUSE-Brazil) has been separated into five major geo-political regions (North, North-East, Centre-West, South-East, and South) to account for regional socio-economic differences, projecting different pathways depending on specific scenarios. For this study, a further ecosystem layer has been characterised. For this, IBGE (IBGE 2018) and FAOSTAT (FAO 2017) data have been used to characterise land use by biome (Fig. 2). Forest land by biome (Fig. 2) has been gathered from the MME (MME 2018), while for regional sugarcane land use UNICA (UNICA 2018) data has been collected.
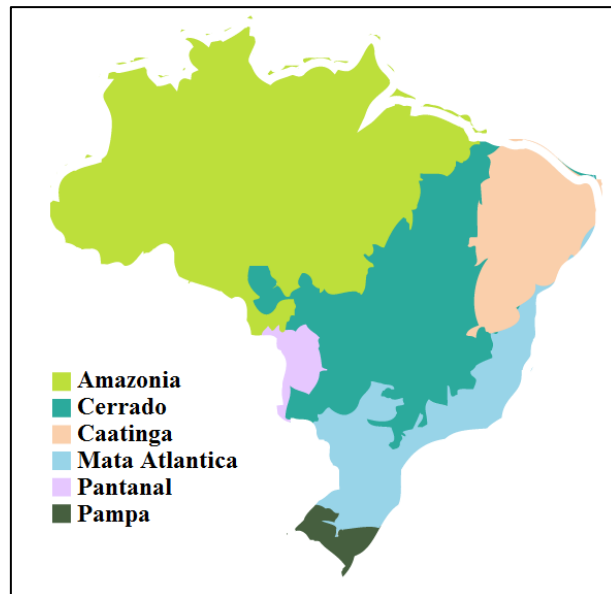

Fig. 2 Brazil's biomes. Source: EMBRAPA (2019)

As biomes can be found in different regions, this has to be characterised in MUSE, as the model's main geographical characterisation is based on Brazil's geopolitical regions. Thus, C stocks per unit area have been considered to calculate total regional C stocks. Table 2 shows the amount of land in each region while Table 3 presents calibrated total land demands by type and by region.

Table 2 Estimated area of natural forest in Brazilian biomes (Adapted from MME (2018)

Biome/Region	North	North-East	Centre-West (Mha)	South-East	South	Total
Amazonia	305.4	2.7	33.6	--	--	341.6
Caatinga	--	41.4	--	--	--	41.4
Cerrado	4.6	18.0	13.5	4.1	0.0	40.3
Mata Atlántica	--	3.4	1.3	11.1	8.3	24.1
Pampa	--	--	--	--	2.8	2.8
Pantanal	--	--	8.9	--	--	8.9
Total	310.0	65.4	57.3	15.2	11.2	459.1

Table 3 Base-year (2010) land use characterisation for the five Brazilian regions

Land type	North	North-East	Centre-West (Mha)	South-East	South	Total
Cropland	3.7	9.6	25.5	20.8	8.2	67.8
Bioenergy [Δ]	0.0	1.1	1.9	6.0	0.7	9.7
Forest	310.0	65.4	57.3	15.2	11.2	459.1
Other natural vegetation	20.3	45.3	0.4	1.1	12.2	79.3
Silviculture	0.3	0.8	0.7	2.9	1.9	6.7
Non-arable	6.7	5.1	4.8	2.5	2.1	21.2
Pasture	45.2	27.2	69.4	36.9	19.1.4	197.8
Urban	1.3	3.8	0.9	5.7	1.8	13.5

[Δ] Only sugarcane is considered

To understand the regional land use differences, Fig. 3 illustrates the share per land type in each region. Large amounts of forest land in most of the regions are noticeable in this figure, particularly in the North and North-East. Cropland and pasture land are more predominant in the Centre-West and South-East, while silviculture is more important in the South-East and South regions. Additionally, the South-East region has the largest amount of sugarcane plantations compared to the rest of the country.
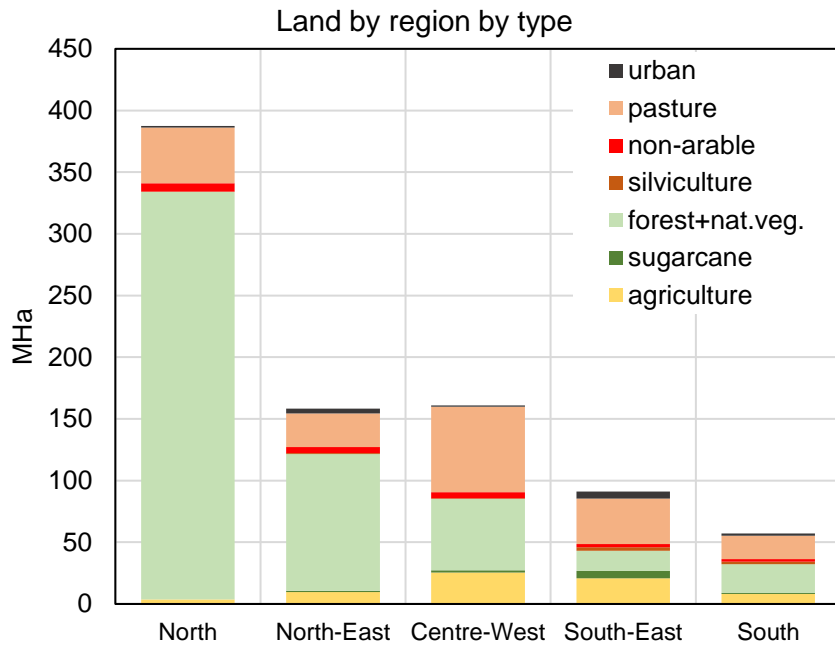
Fig. 3 Land use demand and land use share by region

2.3   Carbon stock characterisation

The forest ecosystems in different biomes play an important role in the Brazilian carbon cycle. Different sources have been used to characterise the C stocks for each biome (IPCC 2006; MMA 2017). Table 4 illustrates the mean values for carbon stocks for each land type used in this research.

Table 4 Total estimated Brazilian land area in 2010 (FAO 2017) and stocks for each carbon pool

Land type	Land Area (Mha)	Above Ground (Mg C ha $^{-1}$)	Below Ground (Mg C ha $^{-1}$)	Dead Organic Matter (Mg C ha $^{-1}$)	Soil Organic Carbon (topsoil layer :0-20 cm) (Mg C ha $^{-1}$)	Total (Mg C ha $^{-1}$)	Source
Cropland	*67.8*	8.0	1.4	n/a	54.0	62.0	Turner et al. (1998)
Pasture	*197.8*	7.6	1.1	n/a	37.3	46.0	Fujisaka et al. (1998)
Forestry prod.[+]	*6.7*	62	12.8	1.8	42	118.6	Stape et al. (2008)
Bioenergy	*9.7*	16	14.3	1.0	33.5	64.8	Miteva et al. (2014)
Amazonia	341.6	176.0	n/a	18.0	104.0	298.0	MMA (2017)
Cerrado	41.4	29.0	23.3	n/a	81.9	134.2	MMA (2017); Schulz et al. (2016)
Caatinga	40.3	42.5	8.5	11.7	38.0	100.7	MMA (2017)
Mata Atlántica	24.1	61.8	14.8	4.1	47.0	127.7	MMA (2017)
Pantanal	2.8	60.2	15.2	5.2	44.0	124.6	MMA (2017)
Pampa	8.9	61.8	14.8	4.1	47.0	127.7	MMA (2017)
Other Nat. vegetation	79.3	6.0	n/a	0	60.0	66.0	Turner et al. (1998)
Non- arable	*21.2*	-	-	-	-	0	
Urban	*13.5*	-	-	-	-	0	

[+]Eucalyptus plantation

9

The total Brazilian carbon stock has been calculated at 135.9 PgC, with the North region representing 70.7%, mainly due to the 310 Mha of the Amazon forest. Considering Turner et al. (1998) study as basis, which calculated the total Brazilian carbon stock at 152.6 PgC in 1990, this means that approximately 11% of the carbon pool were lost between 1990 and 2010. Nevertheless, several uncertainties exist when measuring carbon stocks in different pools. For instance, studies have calculated that only the Amazon, the carbon content lies between 138-348 PgC (Fearnside 2018; Nobre et al. 2016; Quijas et al. 2019). Main differences arise due to application of distinct measurements depths in the soil organic carbon pool.

2.4 Scenarios: Sugarcane expansion or Reforestation

First, a carbon constrained (2 °C) reference scenario is simulated using 2010 as base year with a time-horizon to 2050, to obtain regional liberated land (if any) at each time step (every 5 years). For the reference scenario, a forecast for agricultural commodities has been done using IIASA SSP2 data (Fricko et al. 2017). The SSP2 narrative describes a middle-of-the-road development in mitigation and adaptation. For food and agricultural products demand, which have large implications in land use, regression results suggest that the national food intake will grow from a base-year value of 739 PJ y^{-1} and 232 PJ y^{-1} of crop and animal-based food respectively to about 868 PJ y^{-1} and 300 PJ y^{-1} by 2050 (17.3% increase in food crops and 29.3% in meat products). The regions with the highest demand growth rates are the Centre-West, with a demand increase of 36.5% for food crops and 48.2% for meat, and the North with 34.6% and 45.8% for crops and meat respectively. Total food demand increase by regions can be seen in the Appendix (Table 9).

To calculate land demand, the production increase levels for agricultural crops and meat production has been taken from assumptions made by the Brazilian government (EPE 2016). In general, most of Brazil studies assume that crop yields will grow on average 1.5% per year while meat production will intensify linearly from an average base-year value of 1.0 to 1.7 heads per hectare by 2050. In this study these values have been used as constraints, and the model's technological choice at each period determines the simulated yield growths. Additionally, it has been considered that urban land will not change over time.

Following, the model is applied under two different policy scenarios considering the land and land systems. One scenario explores the expansion of sugarcane on the cleared agricultural land (*sugarcane expansion scenario*), while the second scenario assumes an exclusive reforestation process (*reforestation scenario*).

For sugarcane expansion, endogenous regional yield improvement is considered through intensification of production practices. For the model calibration, regional average yields have been used (UNICA 2018). For future yields projections, it has been assumed that most of the regions will reach by 2050 a maximum value of either the 75th or 95th percentile according to their current baseline values. This acts as a constraint in the model. Fig. 4 shows the current sugarcane yields distribution in ton/ha for the five analysed regions.
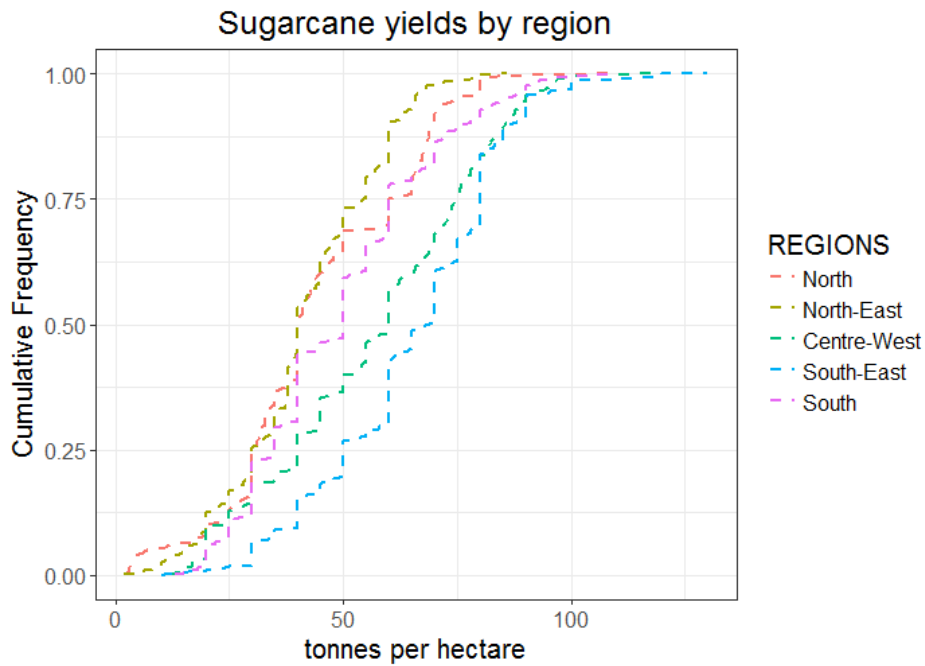
Fig. 4 Regional sugarcane yields distribution for 2015. Source: UNICA *(UNICA 2018)*

Table 5 presents the baseline values used in the calibration as well as the expected maximum yields by the end of the simulation period. The assumed projected yields will be increased within historical projection rates, keeping modelling assumptions realistic.

Table 5 Sugarcane yields for base year and future projections. Source: UNICA (UNICA 2018)

Regions	Percentile 2015	Ton/ha 2015	Percentile 2050	Ton/ha 2050
North	0.29	31.9	0.75	60.0
North-East	0.79	56.0	0.95	66.0
Centre-West	0.40	50.5	0.75	75.0
South-East	0.60	70.4	0.75	80.0
South	0.78	62.3	0.90	77.5

Although some distributions are similar among regions, land use potential for sugarcane expansion vary greatly due to regional biophysical characteristics. New sugarcane expansion has been constrained using Brazil's agro-ecological mapping (MAPA 2009). According to the report, the maximum suitable areas for new sugarcane plantations are located in the Centre-west (30.3 Mha), followed by the South-East (22.7 Mha), South (5.7 Mha), North-East (5.2 Mha) and North (1.1 Mha). These constraints have been considered in the modelling exercise. On the other hand, reforestation is assumed as long as cleared land is available, considering 30-year growing maturity rates affecting the carbon uptake.

11

3. Results

3.1   Reference case

In the reference scenario (Fig. 5), cleared land (available) is mainly represented by former land from crop and pasture. It is expected that agricultural land demand (crops, pasture, bioenergy and silviculture) will peak by 2020 reaching 292 Mha (an increase of 3.5%). Then, due to agricultural intensification, the sector is expected to liberate land at a rate of 6.0% annually, occupying 230 Mha by 2050, thus liberating 68 Mha of land or 8.0% of the total Brazilian territory. Regionally, the Centre-West region, with typical large pasture lands, provides the largest amount of cleared land with 23 Mha, followed by the North (14 Mha) and South-East (13 Mha). Natural forest land, originally comprised by 459 Mha in the base year, would be reduced to 443 Mha by 2050. Most of the reduction arises during the first 15 years (2010-2025), with the Centre-West responsible of 85% (13 Mha) of the total deforestation. The detail of the land demand by region can be seen in the Appendix (Fig. 12).
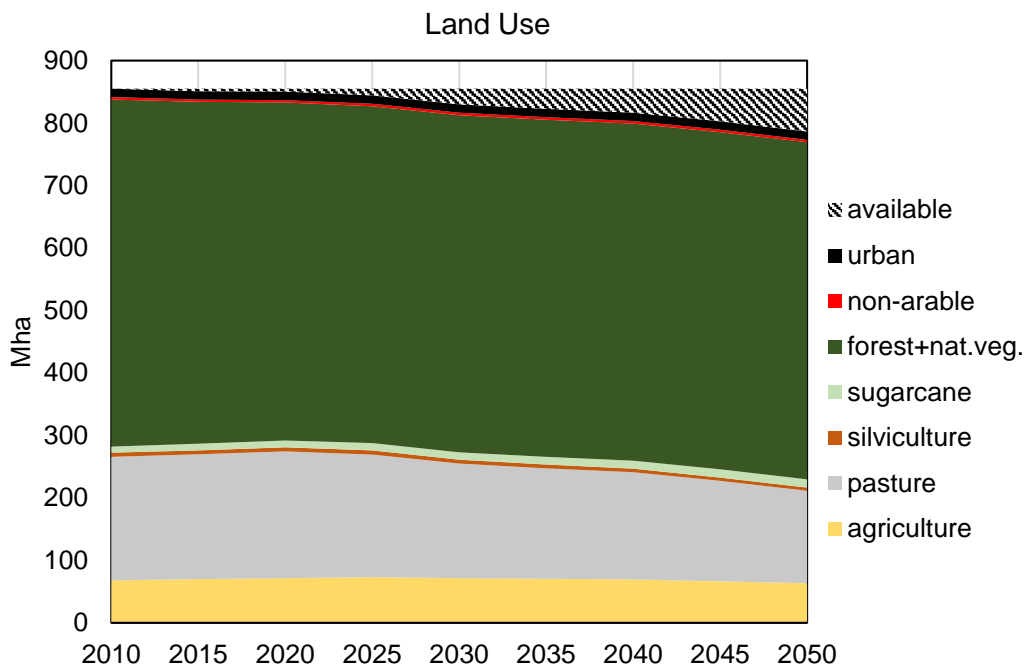

Fig. 5 Land use demand. Reference scenario

Fig. 6 shows the carbon stock dynamics in each region. As the simulation progresses, carbon losses can be appreciated at a rate of 0.1% annually, reducing the national carbon stock from 135.9 PgC in 2010 to 129.9 PgC by 2050. Main carbon emissions arise from agricultural land's SOC pools and loss in above-ground biomass (AB) from deforestation. Regionally, the Centre-West provides the largest losses with 3.5 PgC, followed by the South-East region with 0.7 PgC. By land type, the maximum contributor in C loss is deforestation with 3.4 PgC, followed by pasture lands with 2.3 PgC. On the other hand, thanks to an increase in sugarcane production from 620 to 1,135 MTon and an increase of 38% of land demand, sugarcane land is able to sequester 0.24 PgC by 2050, offsetting

some of its C losses from deforestation. This deforestation occurs when cleared land that becomes available for sugarcane production is not able to entirely cover the sugarcane land expansion in a specific period.
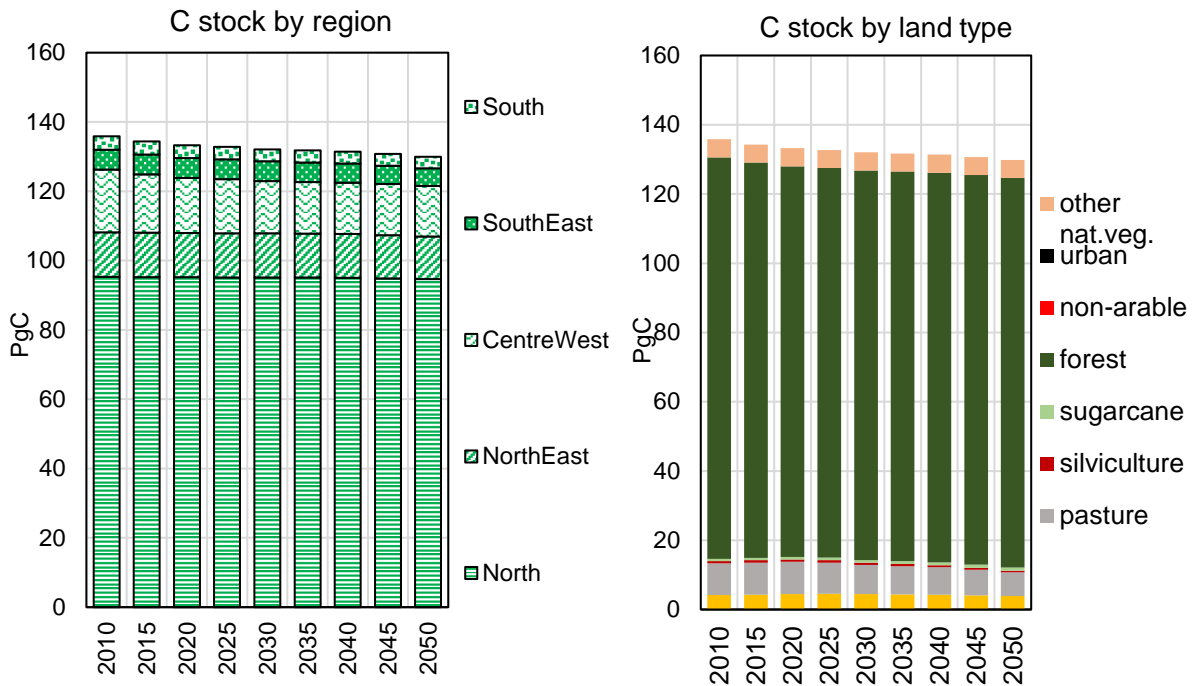

Fig. 6 Carbon stock by region and by land. Reference scenario

Fig. 7 shows the carbon stock changes. All regions contribute to carbon losses at each period to some extent. By land type, the expansion of pasture in the first decade over recent liberated land from cropland and low-carbon forested areas, has contributed to sequester carbon mainly in the SOC pools. In 2030, the model presents a sudden negative C stock change, mainly located in the Centre-West region. The reason is the large quantities of pasture land liberation in the region due to a more intense sector's mechanisation occurring during that period. As shown in Fig. 12 in the Appendix, due to the regional food demand increase (Table 9), during the first 20 years of the simulation (2010-2030), the Centre-West region experiences a rapid increase in pasture land demand having medium-yielding technologies. As the region installs more modern technology and this becomes cheaper in further periods, it becomes available for producers to install high-yielding technologies. Therefore, in later periods, as pasture and crops intensify at different rates in different regions, C losses suffer variations, mainly due to reduction in deforestation rates and the large amount of C flows to the atmosphere previously located in the SOC pools from pasture lands and biomass pools from croplands.
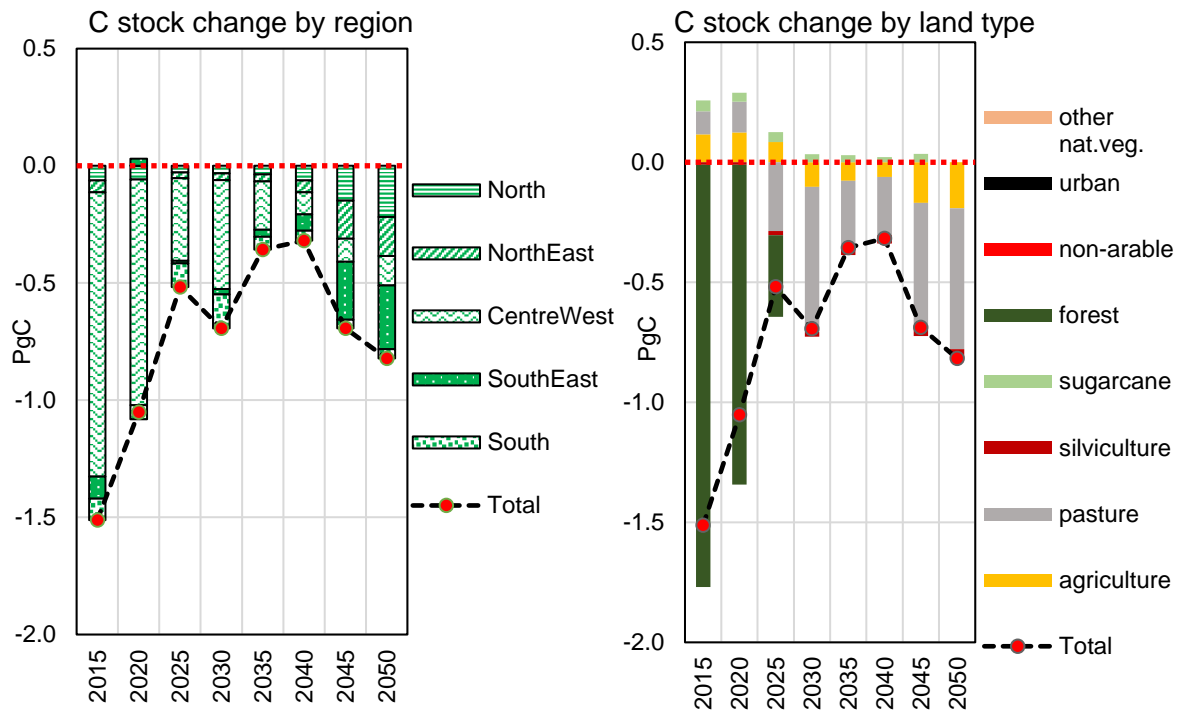
Fig. 7 Carbon change by region and by land. Reference scenario

Nevertheless, the analysis would be incomplete, if the liberated land is not considered further.

3.2   Implications of reforestation or sugarcane expansion

As mentioned in the scenario description, the aim is to study different uses of the liberated land at a regional level and its implication in C sequestration. Fig. 8 shows the C sequestration rates if either a sugarcane expansion or a reforestation scenario is followed.
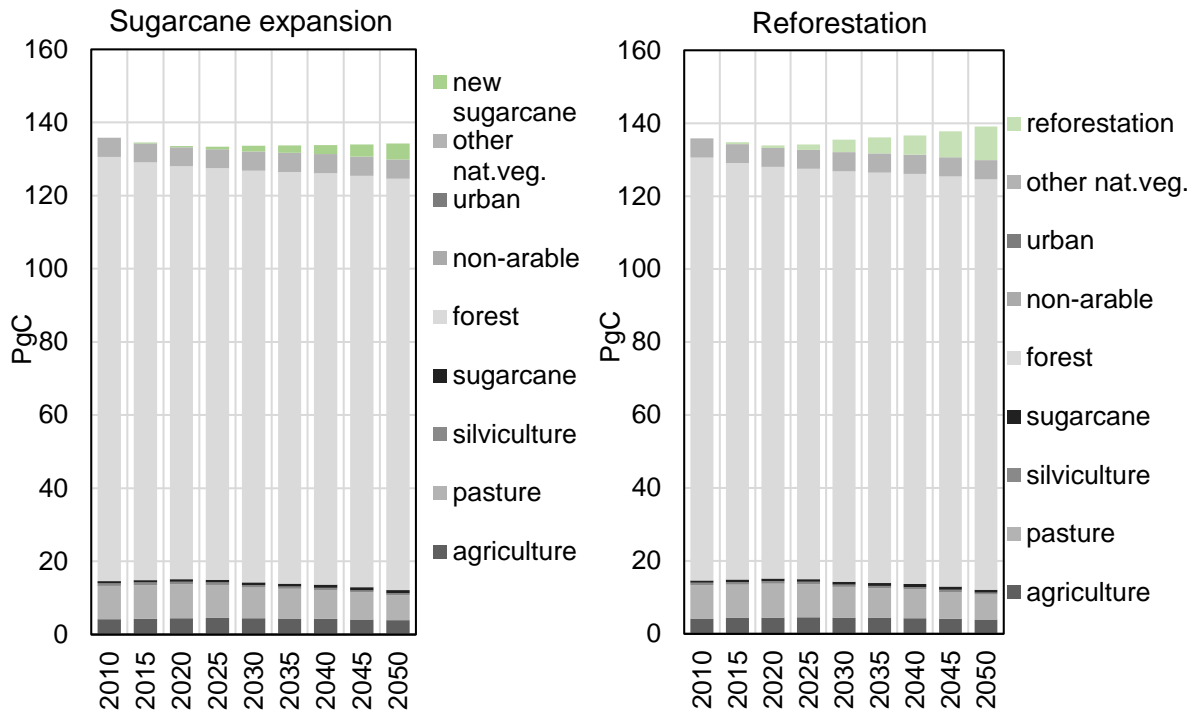
Fig. 8 Carbon stock for sugarcane expansion and reforestation scenarios

Based on the made assumptions, carbon storage and sequestration from reforestation has a larger C sink potential, especially in the Centre-West area. Table 6 and Table 7 depict the intra-period carbon stock for both scenarios for each of the regions. Compared to the reference scenario where available land has been left abandoned and the national carbon stock has been reduced by 4.4%, from 135.9 PgC to 129.9 PgC, if a sugarcane expansion scenario is followed, carbon stock losses would be minimum, only losing 1.2% compared to the baseline value (Table 6). In this scenario, the Centre-West region would still lose 11.3% of its baseline carbon stock. On the other hand, the South-East region would have minimal C increase due to lack of deforestation and large agricultural dynamism. The main reason is the largest amount of sugarcane expansion in the liberated land due to faster intensification of pasture and the higher sugarcane productivity rates per unit area, which in turn results in more C sequestered in biomass pools per hectare.

Table 6 Carbon stock per region for sugarcane expansion scenario

Carbon stock (PgC) – Sugarcane expansion scenario										**%ΔC**
Regions	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	
North	95.3	95.3	95.4	95.4	95.4	95.4	95.4	95.5	95.6	0.3%
North-East	12.8	12.8	12.8	12.8	12.9	12.9	12.9	12.9	13.0	1.1%
Centre-West	18.1	16.9	15.9	15.7	15.9	16.0	16.0	16.0	16.1	-11.3%
South-East	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.9	5.9	2.5%
South	3.9	3.8	3.7	3.8	3.8	3.8	3.8	3.8	3.8	-1.8%
Total	135.9	134.6	133.6	133.5	133.7	133.8	133.9	134.1	134.3	-1.2%

For the reforestation scenario (Table 7), there is a potential to increase national carbon stock by 2.4%, reaching 139.1 PgC by 2050. The increase would mainly come from the Centre-West and South-East regions. On the other hand, the North-East region would decrease C stock due to lower amounts of liberated land combined with a biome (mainly Caatinga biome) with lower carbon content compared to the rest.

Table 7 Carbon stock per region for reforestation scenario

| Regions | Carbon stock (PgC) – Reforestation scenario | | | | | | | | | % ΔC |
	2010	2015	2020	2025	2030	2035	2040	2045	2050	
North	95.3	95.5	95.6	95.7	95.8	95.9	96.0	96.3	96.8	1.6%
North-East	12.8	12.9	12.9	12.9	12.9	13.0	13.0	13.2	13.4	4.7%
Centre-West	18.1	16.9	15.9	15.9	16.9	17.2	17.4	17.6	17.8	-1.4%
South-East	5.8	5.8	5.8	5.8	5.9	5.9	6.0	6.4	6.7	16.8%
South	3.9	3.8	3.7	3.9	4.1	4.2	4.2	4.3	4.3	11.0%
Total	135.9	134.9	134.0	134.3	135.6	136.2	136.7	137.8	139.1	2.4%

Fig. 9 presents the C stock changes at each period for both scenarios. For the sugarcane expansion, net C changes are negative until 2030. This scenario is not able to offset C losses due to deforestation or pasture SOC losses. However, it achieves carbon sequestration rates between 2035 and 2050. Contrarily, the reforestation scenario can act as a sink already by 2025. However, sequestration rates for the next 10 years after 2025 notably decrease due to high losses of SOC pools from pasture land liberation. In the following periods, sequestration rates are recovered, as the model accounts for reforestation in the cleared pasture lands from early years. This effect is due to the forest growth delay, as the model accounts for 30-year growing maturity rates, affecting instantaneous carbon uptake.
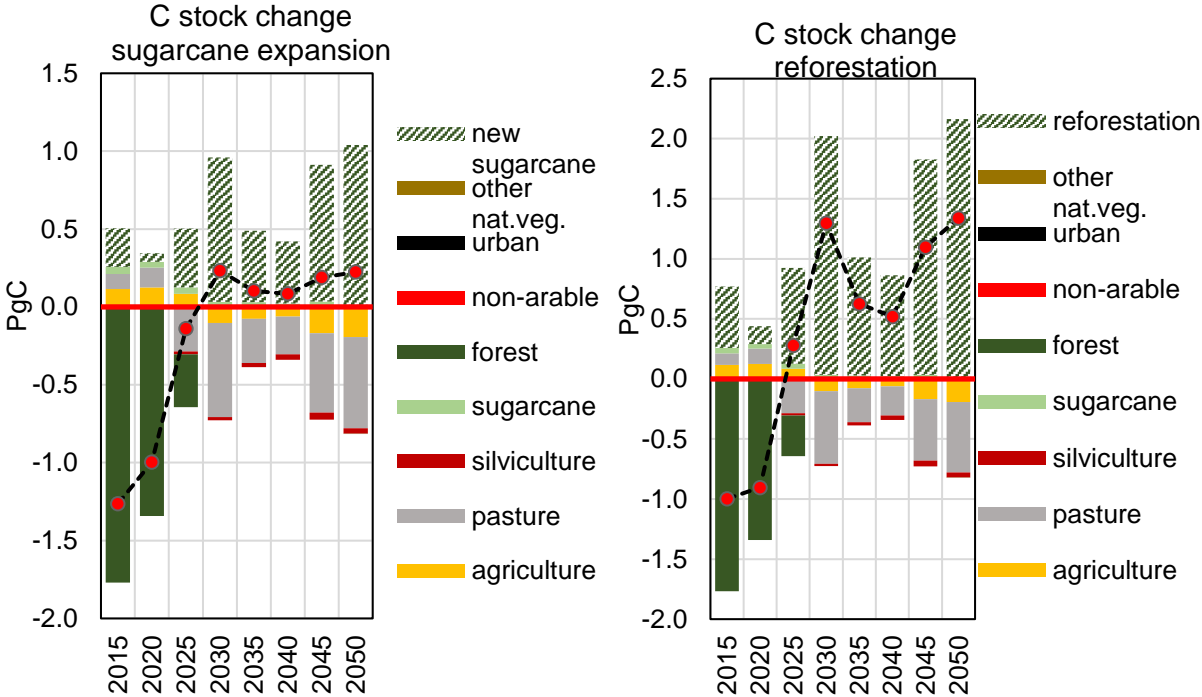

Fig. 9 Carbon change by land stock for sugarcane expansion and reforestation scenarios

Finally, Fig. 10 compares the total carbon stock and the net changes for each scenario compared to the reference case. The reforestation scenario is capable to recover baseline C stocks by 2035, while the sugarcane expansion scenario follows a constant small decrease over the simulation period.
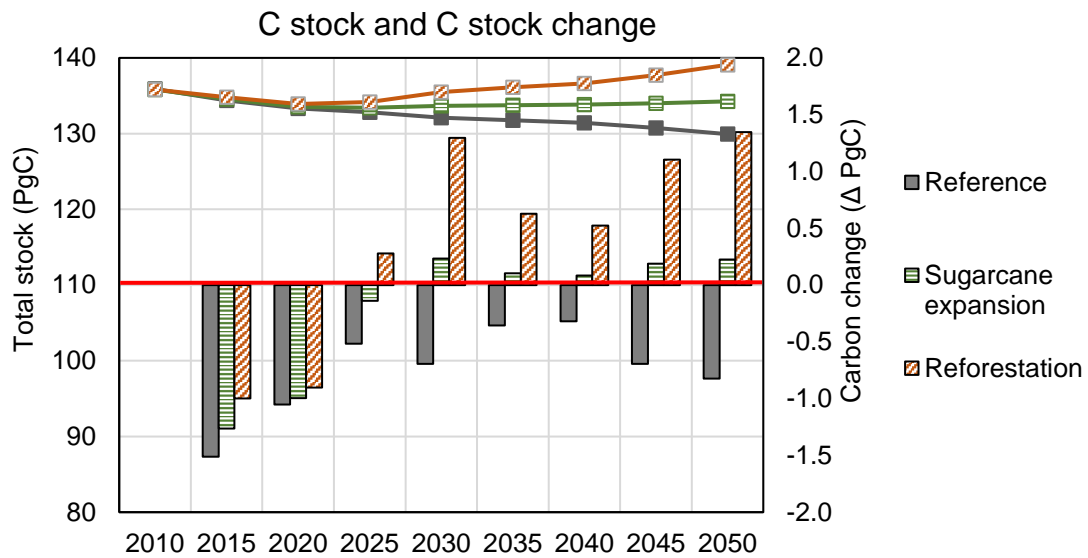

Fig. 10 Scenarios comparison of carbon stock and carbon change

4. Discussions

The potential contributions for carbon sequestration through either sugarcane expansion or reforestation in different regions of Brazil has been studied. Comparison of both scenarios as GHG abatement measures have revealed that large variations exist mainly based on assumed forestry recovery rates, sugarcane production, analysed region and biome, and agricultural commodity demand. Firstly, the model has shown that under a reference scenario and using the SSP2 socioeconomic pathway, due to large investments in modern agricultural technologies and practices, crops and pasture are expected to begin liberating important amounts of land by 2025, particularly in the Centre-West region where a very dynamic agricultural sector exists.

Results from sugarcane sequestration potential are in agreement with Evans et al. (2015), which calculated that sugarcane has a lower GHG offset potential than natural forest recovery, at least for the first 30 years, and even lower than intensive managed reforestation (65 years). However, higher sugarcane yields could improve its GHG abatement potential. In this study, yield improvements have been considered for all regions (Table 5), constraining projections to base-year's high productivity (75th or 95th percentile) levels to avoid infeasible assumptions. Nevertheless, at the end of the analysed period, sugarcane expansion was not able to offset C losses from the land use management and land changes from other lands. Only the North and South-East regions were able to provide minimum C stock reductions. The North region due to the forest removal restrictions set in the model (especially in the Amazon region), while for the South-East, the higher sugarcane yields (~80 ton/ha) provided larger amounts of C stocks per unit area in both biomass pools.

When analysing the reforestation scenario, results indicate that carbon sequestration and storage potential from reforestation either in living biomass or in wood products could provide significant GHG abatement potential, especially in the North (+1.5 PgC), South-East (+1.0 PgC) and North-East (+0.6 PgC) regions. The Centre-West lost -0.3 PgC, mainly from an agricultural sector that is still in expansion and does not liberate agricultural land for the first 20 years, therefore deforestation still occurs. Added to that, when cleared land is available (mostly after 2035), the region has the lowest C succession rates from reforestation due to a lower carbon content forest by unit area such as the Cerrado forest.

Both scenarios presented could be regarded as hypothetical cases due to ecosystem or economic constraints. The later especially applies to sugarcane expansion, with a limited global market for sugarcane by-products such as sugar and ethanol. Fig.11 illustrates the maximum sugar and ethanol production potential from the sugarcane expansion scenario. Outputs show that by 2030 there is a maximum potential to produce around 1,600 MTon of sugarcane, and by 2050 this could increase to 5,200 MTon. This value is five-fold compared to what is expected in the reference scenario of 1,121 MTon. Also, high production in the North region might be infeasible due to the climatic characteristics of the Amazon, an ecosystem with lack of dry periods needed for sugarcane growth. However, recently new genetically modified (GM) sugarcane breeds have been tested that could provide producers in year-round humid regions with cost-effective sugarcane crops. Under current production levels and feedstock share dedicated to either sugar or ethanol, the hypothetical outputs represent the production of 324 MTon of sugar and 214 billion litres of ethanol by 2050. To put this into perspective, in 2015 Brazil produced 34 MTon of sugar and 30 billion litres of ethanol. Globally, the overall production stands at about 180 MTon for sugar and 100 billion litres of ethanol. The aforementioned production (214 billion litres) has the capacity to reduce around 0.38 $GtCO_2$/year from gasoline utilisation in the transport sector.
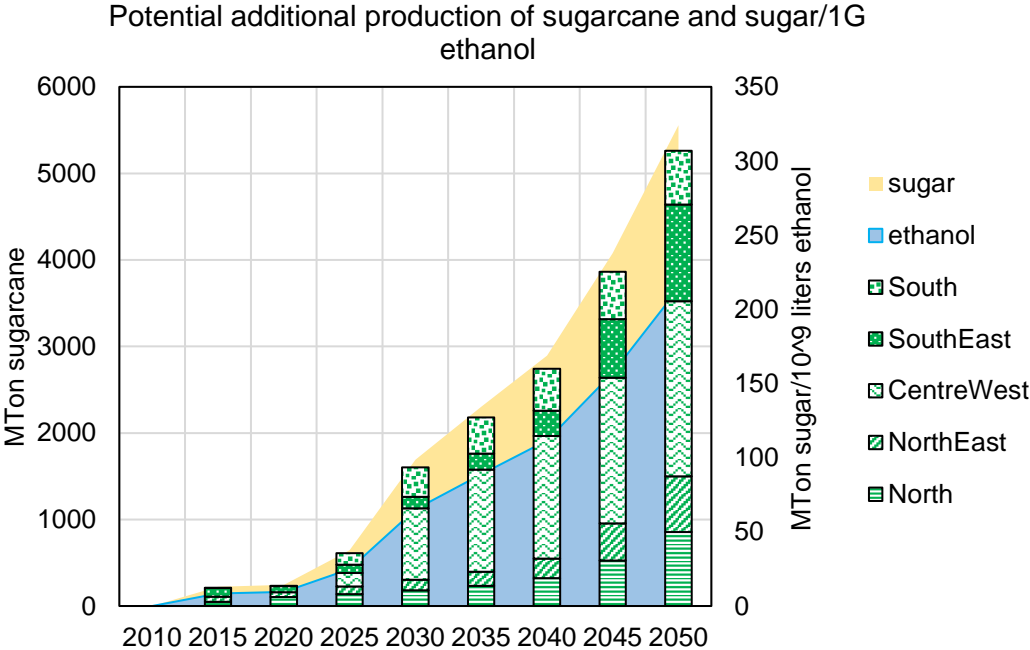

Fig. 11 Maximum sugarcane production by region and sugar/ethanol production potential

Additionally, the Brazilian government has limited the amount of area where sugarcane can be expanded. This is about 64 Mha, mainly from current agricultural land in the South-East and Centre-West regions. The total liberated land by 2050 estimated by the model (~68 Mha) is close to the limits suggested by the government; however, the model presented in this study is not capable to spatially explicitly locate if the liberated land is potentially suitable for sugarcane expansion, as located by the Brazilian authorities.

5. Conclusion

Due to increase in food demands, land competition and deforestation rates, the AFOLU sector would face some high environmental degradation, posing a risk in achieving global mitigation targets. In this paper we have expanded the energy system model MUSE allowing to investigate the carbon sequestration and storage potential from either bioenergy growth (in the form of sugarcane crops) or reforestation.

The model reference scenario has shown that Brazil has the potential to liberate up to 32.3 Mha of agricultural land by 2035 (mainly from pasture intensification in the Centre-West region) and by 2050 this could reach 68.4 Mha. If this land is abandoned, the country's carbon stock could be reduced from 135.9 PgC in 2010 to 129.9 PgC by 2050. If a sugarcane expansion policy is followed, by mid-century the carbon stock could be recovered to 134.2 PgC, mainly due to the C sequestration in the above and below ground biomass pools; however, it would not be able to recover to baseline C stock value. On the other hand, a reforestation-only scenario projects that by 2035 the baseline year C stock could be recovered and by 2050 it would be increased by 3.3 PgC, reaching positive annual sequestration rates of +0.1 PgC y^{-1}. C sequestration is mainly supported by the South-East and North. Brazil's tropical ecosystems, where tree forests have rapid growth rates, have the potential to become one of the largest GHG abatement regions in the world thanks due to its high C sequestration rates.

For any policy programme, both scenarios could be regarded as aggressive strategies that might not be sustainable. The uncontrolled expansion of sugarcane due to sugar and ethanol demand increase could lead to greater impacts on soil organic carbon (SOC) stocks as well as NOx emissions due to larger amounts of fertiliser used. Also, food prices could be affected due to lower available land for food cropping purposes. Yet, one of the main advantages of sugarcane expansion that was not discussed in the paper is the GHG emissions offset potential from sugarcane ethanol when it removes fossil-fuel based gasoline from the market. Nevertheless, appropriate bioenergy emissions account, especially those related to indirect land use remain to be investigated.

Carbon budgets and carbon policies often neglect the potential of forest and land use management. The obtained results suggest that reforestation should be regarded as an option for carbon mitigation as important as BECCS. But even though reforestation presented larger C sequestration potentials in this study, it also presents compromises between biodiversity, C sequestration and water usage. If well managed, reforestation could be an important measure to reduce and reverse biodiversity loss, otherwise it could also cause environmental degradation by altering precipitation, soil moisture and soil erosion. Although not analysed in this study, sugarcane-based ethanol production with CCS could hold an even greater potential to minimise energy emissions, increase energy security, and reduce dependency of fossil fuels at a local and global level. Nevertheless, for this to happen, CCS technologies still need to become economically attractive either through technology cost reduction, commercialisation of captured CO2 (e.g. EOR) or government incentives.

GHG mitigation potential of either scenario should not be generalized as several limitations to this study should be considered when analysing the results. Uncertainty arises mainly from the model structure and assumptions made, especially in the carbon stocks and carbon changes due to land use management. Also, it is suggested that frameworks to estimate C pools and fluxes need to be standardised. This is fundamental if polices addressing forest C sequestration are going to be put in place. As MUSE is primarily an energy system model, for future work, a comparison of cost and technical implementation of industrial CCS and carbon capture from reforestation and land use management will be studied in more detail. Also, Nitrogen cycles dynamics during tropical reforestation and sugarcane growth will be quantified.

Acknowledgements

Nomenclature

AB	above ground biomass
BB	below ground biomass
C	carbon
DOM	dead organic matter
GDP_{cap}	gross domestic product per capita
l	carbon pool
LU	land use

References

Albanito F, Beringer T, Corstanje R, Poulter B, Stephenson A, Zawadzka J, Smith P (2016) Carbon implications of converting cropland to bioenergy crops or forest for climate mitigation: a global assessment GCB Bioenergy 8:81-95 doi:10.1111/gcbb.12242

Azar C et al. (2010) The feasibility of low CO2 concentration targets and the role of bio-energy with carbon capture and storage (BECCS) Climatic Change 100:195-202 doi:10.1007/s10584-010-9832-7

Crow DJG, Giarola S, Hawkes AD (2018) A dynamic model of global natural gas supply Applied Energy 218:452-469 doi:https://doi.org/10.1016/j.apenergy.2018.02.182

De Oliveira Silva R, Barioni LG, Queiroz Pellegrino G, Moran D (2018) The role of agricultural intensification in Brazil's Nationally Determined Contribution on emissions mitigation Agricultural Systems 161:102-112 doi:https://doi.org/10.1016/j.agsy.2018.01.003

Deng YY, Koper M, Haigh M, Dornburg V (2015) Country-level assessment of long-term global bioenergy potential Biomass and Bioenergy 74:253-267 doi:https://doi.org/10.1016/j.biombioe.2014.12.003

Dwivedi P, Khanna M, Sharma A, Susaeta A (2016) Efficacy of carbon and bioenergy markets in mitigating carbon emissions on reforested lands: A case study from Southern United States Forest Policy and Economics 67:1-9 doi:https://doi.org/10.1016/j.forpol.2016.03.002

EMBRAPA (2019) Biomas do Brasil - Empresa Brasileira de Pesquisa Agropecuária (Embrapa).

EPE (2016) Plano Nacional de Energia - 2050. Ministerio de Minas e Energia, Rio de Janeiro, Brazil

Evans SG, Ramage BS, DiRocco TL, Potts MD (2015) Greenhouse Gas Mitigation on Marginal Land: A Quantitative Review of the Relative Benefits of Forest Recovery versus Biofuel Production Environmental Science & Technology 49:2503-2511 doi:10.1021/es502374f

FAO (2017) FAOSTAT. Accessed 10 August 2017

Fearnside PM (2018) Brazil's Amazonian forest carbon: the key to Southern Amazonia's significance for global climate Regional Environmental Change 18:47-61 doi:10.1007/s10113-016-1007-2

Freitas FF et al. (2019) The Brazilian market of distributed biogas generation: Overview, technological development and case study Renewable and Sustainable Energy Reviews 101:146-157 doi:https://doi.org/10.1016/j.rser.2018.11.007

Fricko O et al. (2017) The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century Global Environmental Change 42:251-267 doi:https://doi.org/10.1016/j.gloenvcha.2016.06.004

Fujisaka S, Castilla C, Escobar G, Rodrigues V, Veneklaas EJ, Thomas R, Fisher M (1998) The effects of forest conversion on annual crops and pastures:: Estimates of carbon emissions and plant species loss in a Brazilian Amazon colony Agriculture, Ecosystems & Environment 69:17-26 doi:https://doi.org/10.1016/S0167-8809(98)00091-7

García Kerdan I, Giarola S, Hawkes A (2019) A novel energy systems model to explore the role of land use and reforestation in achieving carbon mitigation targets: A Brazil case study Journal of Cleaner Production In Press, Accepted Manuscript doi:https://doi.org/10.1016/j.jclepro.2019.05.345

Guo LB, Gifford RM (2002) Soil carbon stocks and land use change: a meta analysis Global Change Biology 8:345-360 doi:10.1046/j.1354-1013.2002.00486.x

Haberl H, Beringer T, Bhattacharya SC, Erb K-H, Hoogwijk M (2010) The global technical potential of bio-energy in 2050 considering sustainability constraints Current Opinion in Environmental Sustainability 2:394-403 doi:https://doi.org/10.1016/j.cosust.2010.10.007

Hasegawa T, Matsuoka Y (2010) Global methane and nitrous oxide emissions and reduction potentials in agriculture Journal of Integrative Environmental Sciences 7:245-256 doi:10.1080/19438151003621367

IBGE (2018) Natural Resources and Environmental Studies - Coverage and Land Use (Recursos Naturais e Estudos Ambientais - Cobertura e Uso da Terra). https://ww2.ibge.gov.br/home/geociencias/recursosnaturais/usodaterra/default.shtm. Accessed 01/04/2018 2018

IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories. UNEP,

IPCC (2014) Climate change 2014: Mitigation of Climate Change Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. United Kingdom and New York, NY, USA

Krause A et al. (2017) Global consequences of afforestation and bioenergy cultivation on ecosystem service indicators Biogeosciences 14:4829-4850 doi:10.5194/bg-14-4829-2017

Kraxner F, Nilsson S, Obersteiner M (2003) Negative emissions from BioEnergy use, carbon capture and sequestration (BECS)—the case of biomass production by sustainable forest management from semi-natural temperate forests Biomass and Bioenergy 24:285-296 doi:https://doi.org/10.1016/S0961-9534(02)00172-1

MAPA (2009) Zoneamento Agroecológico da Cana-de-açúcar (ZAECana). Rio de Janeiro, RJ, Brazil

Minx JC, Lamb WF, Callaghan MW, Bornmann L, Fuss S (2017) Fast growing research on negative emissions Environmental Research Letters 12:035007

Miteva DA, Kennedy CM, Baumgarten L (2014) Carbon biophysical parameters applied to the Brazilian Cerrado.

MMA (2017) Brazil's Forest Reference Emission Level for Reducing Emissions from Deforestation in the Cerrado biome for Results-based Payments for REDD+ under the United Nations Framework Convention on Climate Change vol Working Group of Technical Experts on REDD+. Brasilia, df, Brazil

MME (2018) PROBIO - Project for the conservation and sustainable use of Brazilian biological diversity (Projeto de conservação e utilização sustentável da diversidade biológica Brasileira), Ministry of the Environment (Ministerio de Meio Ambiente). Accessed 10/04/2018 2018

Moreira JR, Romeiro V, Fuss S, Kraxner F, Pacca SA (2016) BECCS potential in Brazil: Achieving negative emissions in ethanol and electricity production based on sugar cane bagasse and other residues Applied Energy 179:55-63 doi:https://doi.org/10.1016/j.apenergy.2016.06.044

Muratori M, Calvin K, Wise M, Kyle P, Edmonds J (2016) Global economic consequences of deploying bioenergy with carbon capture and storage (BECCS) Environmental Research Letters 11:095004

Ni Y, Eskeland GS, Giske J, Hansen J-P (2016) The global potential for carbon capture and storage from forestry Carbon Balance and Management 11:3 doi:10.1186/s13021-016-0044-y

Nijsen M, Smeets E, Stehfest E, Vuuren DP (2012) An evaluation of the global potential of bioenergy production on degraded lands GCB Bioenergy 4:130-147 doi:doi:10.1111/j.1757-1707.2011.01121.x

Nobre CA, Sampaio G, Borma LS, Castilla-Rubio JC, Silva JS, Cardoso M (2016) Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm Proceedings of the National Academy of Sciences 113:10759 doi:10.1073/pnas.1605516113

Plevin RJ, O'Hare M, Jones AD, Torn MS, Gibbs HK (2010) Greenhouse Gas Emissions from Biofuels' Indirect Land Use Change Are Uncertain but May Be Much Greater than Previously Estimated Environmental Science & Technology 44:8015-8021 doi:10.1021/es101946t

Quijas S et al. (2019) Modelling carbon stock and carbon sequestration ecosystem services for policy design: a comprehensive approach using a dynamic vegetation model Ecosystems and People 15:42-60 doi:10.1080/26395908.2018.1542413

Raphael Slade, Robert Saunders, Robert Gross, Bauen A (2011) Energy from biomass: the size of the global resource. Imperial College Centre for Energy Policy and Technology and UK Energy Research Centre, London, UK

Scherer LA, Verburg PH, Schulp CJE (2018) Opportunities for sustainable intensification in European agriculture Global Environmental Change 48:43-55 doi:https://doi.org/10.1016/j.gloenvcha.2017.11.009

Schulz K, Voigt K, Beusch C, Almeida-Cortez JS, Kowarik I, Walz A, Cierjacks A (2016) Grazing deteriorates the soil carbon stocks of Caatinga forest ecosystems in Brazil Forest Ecology and Management 367:62-70 doi:https://doi.org/10.1016/j.foreco.2016.02.011

Silver WL, Ostertag R, Lugo AE (2000) The Potential for Carbon Sequestration Through Reforestation of Abandoned Tropical Agricultural and Pasture Lands Restoration Ecology 8:394-407 doi:10.1046/j.1526-100x.2000.80054.x

Smeets EMW, Faaij APC, Lewandowski IM, Turkenburg WC (2007) A bottom-up assessment and review of global bio-energy potentials to 2050 Progress in Energy and Combustion Science 33:56-106 doi:https://doi.org/10.1016/j.pecs.2006.08.001

Smith P et al. (2013) How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? Global Change Biology 19:2285-2302 doi:doi:10.1111/gcb.12160

Stape JL, Binkley D, Ryan MG (2008) Production and carbon allocation in a clonal Eucalyptus plantation with water and nutrient manipulations Forest Ecology and Management 255:920-930 doi:https://doi.org/10.1016/j.foreco.2007.09.085

Turner D, Winjum JK, Kolchugina TP, Vinson TS, Schroeder PE, Phillips DL, Cairns M (1998) Estimating the terrestrial carbon pools of the former Soviet Union, conterminous U.S., and Brazil vol 9. doi:10.3354/cr009183

UN (2015) Framework Convention on Climate Change: Adoption of the Paris Agreement. United Nations, 21st Conference of the Parties, Paris

UNICA (2018) Unicadata - Brazilian Sugarcane Industry Association. Accessed 03/03/2018 2018

Yue Q, Xu X, Hillier J, Cheng K, Pan G (2017) Mitigating greenhouse gas emissions in agriculture: From farm production to food consumption Journal of Cleaner Production 149:1011-1019 doi:https://doi.org/10.1016/j.jclepro.2017.02.172

Appendix

Table 8 Soil carbon stock mean value response to different land sue changes. Source: Guo and Gifford (2002)

Land use Origin	Land use Destination	Δ SOC
Forest	*Pasture*	8%
Pasture	*Secondary Forest*	-20%
Pasture	*Silviculture*	-10%
Forest	*Silviculture*	-13%
Crop	*Silviculture*	18%
Forest	*Crop*	-42%
Crop	*Secondary Forest*	53%
Pasture	*Crop*	-59%
Crop	*Pasture*	19%

Table 9 Projection of regional crop and meat products demand in Brazil

| Regions	2010 crops PJ $^{y-1}$	2010 meat PJ $^{y-1}$	2030 crops PJ $^{y-1}$	2030 meat PJ $^{y-1}$	2050 crops PJ $^{y-1}$	2050 meat PJ $^{y-1}$	(2050/2010) crops % change	(2050/2010) meat % change
North	61.0	18.4	76.7	23.9	82.1	26.8	34.6%	45.8%
North-East	203.0	59.1	226.3	69.5	230.0	74.4	13.3%	25.8%
Centre-West	54.6	17.7	69.9	23.5	74.6	26.3	36.5%	48.2%
South-East	314.1	102.7	355.1	121.5	359.0	129.3	14.3%	25.9%
South	106.7	34.2	121.0	40.8	121.9	43.3	14.3%	26.6%
Total	**739.3**	**232.1**	**849.1**	**279.2**	**867.5**	**300.0**	**17.3%**	**29.3%**
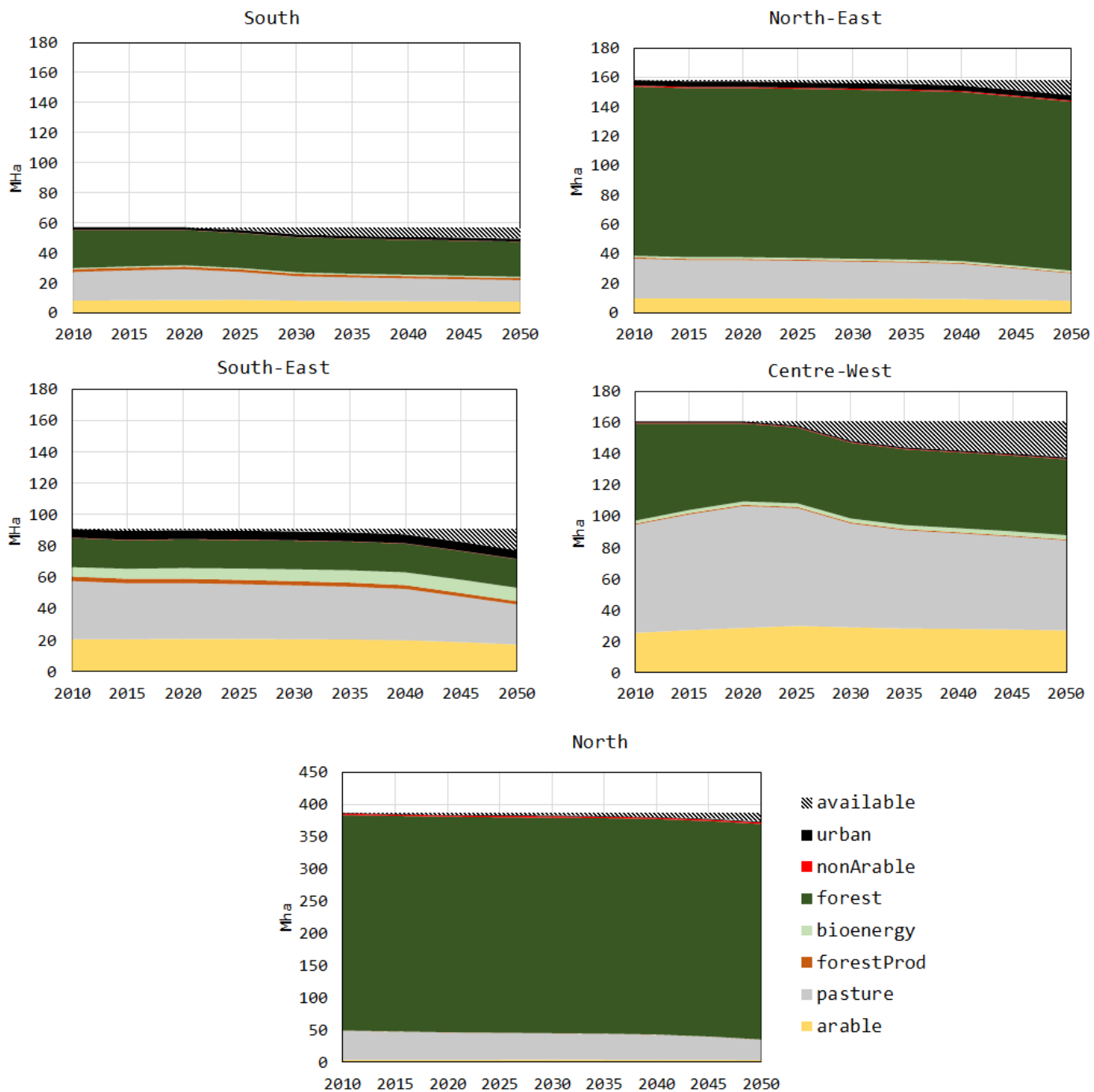
Fig. 12 Land use demand by regions. Reference scenario