

GEANDERSON EDUARDO AMBRÓSIO

**BRAZILIAN FUTURE LAND-USE DYNAMICS AND IMPACTS OF  
DEFORESTATION POLICIES**

Tese apresentada à Universidade Federal de Viçosa, como parte das exigências do Programa de Pós-Graduação em Economia Aplicada, para obtenção do título de Doctor Scientiae.

VIÇOSA  
MINAS GERAIS - BRASIL  
2019

**Ficha catalográfica preparada pela Biblioteca Central da Universidade  
Federal de Viçosa - Câmpus Viçosa**

T

A496l  
2019 Ambrósio, Geanderson Eduardo, 2019-  
Brazilian future land-use dynamics and impacts of  
deforestation policies / Geanderson Eduardo Ambrósio. –  
Viçosa, MG, 2019.  
ix, 100f. : il. (algumas color.) ; 29 cm.

Texto em inglês.

Inclui apêndices.

Orientador: Dênis Antônio da Cunha.

Tese (doutorado) - Universidade Federal de Viçosa.

Referências bibliográficas: f.78-87.

1. Desmatamento. 2. Solos - Uso. 3. Agricultura - Aspectos ambientais. 4. Brasil. I. Universidade Federal de Viçosa. Departamento de Economia Rural. Programa de Pós-Graduação em Economia Aplicada. II. Título.

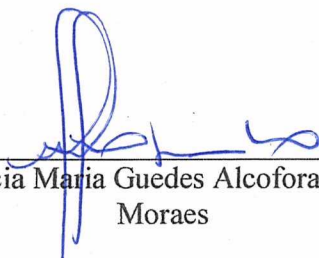
CDD 22 ed. 333.75130981

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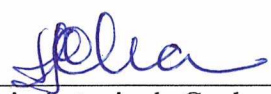
APROVADA: 03 de junho de 2019.

  
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“Live today, love tomorrow, unite forever.”

Tomorrowland

## CONTENTS

LIST OF ABBREVIATIONS.....	viii
ABSTRACT.....	viii
RESUMO.....	ix
1. INTRODUCTION.....	1
1.1. Research Questions.....	1
1.2. Thesis structure.....	2
1.3. Land-use change dynamics.....	3
1.3.1. Agriculture and deforestation.....	3
1.3.2. Impacts of mitigation.....	5
1.4. Land-use Dynamics in Brazil.....	9
1.4.1. Historical contextualization of Brazilian agriculture.....	9
1.4.2. Deforestation policies for Legal Amazon and Cerrado.....	11
1.4.3. Assessing land use and leakage.....	14
2. MATERIAL AND METHODS.....	21
2.1. MAgPIE modeling framework.....	21
2.2. Preprocessing of input data.....	22
2.2.1. Grid level input data.....	22
2.2.2. Clusterization.....	23
2.2.3. Socioeconomic input data and regional setup.....	23
2.3. Model run – main features.....	24
2.3.1. The cost minimization function.....	27
2.3.2. Land-use change and deforestation.....	28
2.3.3. National Policies Implemented (NPIs).....	31
2.4. Biophysical and Socioeconomic scenario-based analysis.....	32
3. RESULTS AND DISCUSSION.....	36
3.1. Brazilian future land-use dynamics.....	36
3.1.1. Food and feed demand.....	36
3.1.2. Natural Land.....	38
3.1.3. LUC CO2 Emissions.....	41
3.1.4. Agricultural Land.....	42
3.1.5. Production, yields, trade, and price.....	45
3.1.6. Summary of results.....	50
3.1.7. Discussion.....	50
3.2. Impacts of Brazilian deforestation policies.....	57
3.2.1. Natural Land.....	57

3.2.2. LUC CO2 Emissions.....	62
3.2.3. Agricultural Land.....	64
3.2.4. Production, yields, trade, and price.....	69
3.2.5. Summary of results .....	73
3.2.6. Discussion .....	74
4. CONCLUSIONS.....	78
REFERENCES.....	82
APPENDIX 1 .....	93
APPENDIX 2.....	94

## LIST OF ABBREVIATIONS

AFOLU	Agriculture, Forestry And Other Land Use
BLUM	Brazilian Land Use Model
CO <sub>2</sub>	Carbon dioxide
DETER	Real-Time Deforestation Detection Project
DM	Dry Matter
FAO	Food And Agriculture Organization Of The United Nations
GHG	Greenhouse Gas
Gt	Gigaton
ha	Hectare
IBGE	Instituto Brasileiro De Geografia E Estatística
INPE	Instituto Nacional De Pesquisas Espaciais
IPCC	Intergovernmental Panel On Climate Change
LPJmL	Lund-Potsdam-Jena Managed Land
LUC	Land-Use Change
LUH2	Land-Use Harmonization 2
MAgPIE	Model Of Agricultural Production And Its Impact On The Environment
Mt	Megaton
NDC	Nationally Determined Contribution
NPCC	National Policy On Climate Change
NPIs	National Policies Implemented
PA	Protected Areas
PPCDAm	Plano De Ação Para Prevenção E Controle Do Desmatamento Na Amazônia Legal
PPCerrado	Plano De Ação Para Prevenção E Controle Do Desmatamento E Das Queimadas No Cerrado
RCP	Representative Concentration Pathway
SSP	Socioeconomic Shared Pathway
t	Ton
TFP	Total-Factor Productivity
UNFCCC	United Nations Framework Convention On Climate Change
yr	Year

## ABSTRACT

AMBRÓSIO, Geanderson Eduardo. Universidade Federal de Viçosa, June 2019. **Brazilian future land-use dynamics and impacts of deforestation policies**. Advisor: Dênis Antônio da Cunha.

Land use interacts with a dichotomous relationship between agricultural production and forest conservation, it depends on socioeconomic and biophysical features, and it has time and geographic specific dynamics. National environmental policies can drive national land-use change (LUC) and, due to interconnected global markets, it affects international land dynamics in positive or negative ways. The present research uses a global land-use model to assess Brazilian land-use dynamics by projecting and evaluating i) Brazilian LUC over this century and ii) the national and international impacts of Brazilian deforestation policies over 2050. Results on LUC over this century suggest that Brazilian land use can evolve in diverse pathways depending on the socioeconomic and biophysical assumptions. Pastureland presents an important decrease in the next decades while cropland takes over it and keeps increasing up to 2040, especially in the South and Northeast. Deforestation and depletion of natural land fade out in the next decades and this dynamic can be due to the abandonment of pasturelands and to policies to reduce deforestation. If the world tracks the path to stay below the 2-degree warming, Brazil would benefit of the establishment of a biofuel market by producing and exporting bioenergy crops, but at the cost of increased food prices due to higher land competition. Results on the impacts of deforestation mitigation revealed that these policies have a major impact on reducing deforestation in Brazil. Mitigation policies for Legal Amazon and Cerrado present a net saving of up to 50 million ha of forestland from 1995 to 2050 and are associated with higher crop yields. This policy promotes agricultural reallocation to other countries, resulting in deforestation and Carbon emissions in these countries, but such effects are lower than the Brazilian mitigation. This counterbalancing demonstrates that Brazil's mitigation results are higher than its effective contribution to global mitigation. By one side, the diverse land-use pathways to 2100 suggest that Brazil may still have time to drive its LUC according to its interests. However, as relative global results are lower than the individual Brazilian achievement, the time that Brazil may still have to act and drive its land use may also be used to design cooperative international policies in order to enhance global effectiveness.

## RESUMO

AMBRÓSIO, Geanderson Eduardo. Universidade Federal de Viçosa, June 2019. **Brazilian future land-use dynamics and impacts of deforestation policies**. Orientador: Dênis Antônio da Cunha.

O uso da terra interage com a relação dicotômica entre produção agrícola e a conservação da floresta, depende de características socioeconômicas e biofísicas, e possui dinâmicas específicas de tempo e geográficas. Políticas ambientais nacionais podem determinar mudanças de uso da terra em nível nacional e, devido a mercados globais interconectados, afetam também essa dinâmica em nível internacional, de formas positivas ou negativas. A presente pesquisa usa um modelo global de uso da terra para i) projetar e avaliar a dinâmica brasileira de uso da terra ao longo deste século e ii) os impactos nacionais e internacionais das políticas brasileiras de desmatamento até 2050. Os resultados sugerem que o uso da terra no Brasil pode evoluir em diversos caminhos, dependendo dos pressupostos socioeconômicos e biofísicos. A área de pastagem reduz nas próximas décadas, enquanto a área agrícola expande sobre pastagens abandonadas até 2040, especialmente no sul e nordeste. O desmatamento e depleção de áreas naturais reduz e se estabiliza nas próximas décadas e essa dinâmica pode ser devido ao abandono das pastagens e às políticas de redução do desmatamento. Caso siga-se as trajetórias que mantêm a temperatura média global abaixo de 2 graus, o Brasil se beneficiaria do estabelecimento de um mercado de biocombustíveis produzindo e exportando culturas de bioenergia, mas em um cenário de aumento dos preços dos alimentos devido à maior competição agrícola. Os resultados sobre a política desmatamento na Amazônia Legal e Cerrado contribuem com uma preservação líquida de até 50 milhões de hectares de florestas entre 1995 e 2050. Tal política promove também realocação agropecuária para outros países, resultando em desmatamento e emissões de Carbono nesses países, porém estes efeitos não são maiores que a mitigação brasileira. Esse contrapeso demonstra que os resultados de mitigação do Brasil são mais altos do que sua contribuição efetiva para a mitigação global. Por um lado, os diversos caminhos de uso da terra até 2100 sugerem que o Brasil ainda pode ter tempo para conduzir suas mudanças de uso da terra de acordo com seus melhores interesses. No entanto, como os resultados globais relativos são mais baixos do que os resultados individuais brasileiros, o tempo que o Brasil ainda pode ter para agir e direcionar seu uso da terra também deve ser usado para desenvolver políticas internacionais cooperativas de mitigação a fim de aumentar a eficácia global dessas políticas.

# 1. INTRODUCTION

## 1.1. Research Questions

Land system dynamics face challenges from agricultural production and forest conservation and depends on socioeconomic (POPP et al., 2017) and biophysical (VAN VUUREN et al., 2011) features. The prior knowledge on how the land-use change (LUC) dynamics should evolve enable future tailor-made policies, minimizing potential undesired effects and improving its effectiveness (KAREIVA et al., 2007). National environmental policies drive national land-use change dynamics, but can also affect global land-use patterns due to agricultural relocation and leakage effects (HENDERS; OSTWALD, 2014). The Brazilian government has unleashed efforts towards reducing deforestation and driving LUC in Legal Amazon<sup>1</sup> (BRASIL, 2018a) and Cerrado (BRASIL, 2016). Nonetheless, the national and global impacts of reducing deforestation in those areas remain unclear. Assessments of the impacts of reducing deforestation and other land-use dynamics should account for international trade in agricultural and forest commodities (MEYFROIDT; RUDEL; LAMBIN, 2010) in order to represent agricultural relocation and leakage. The present research uses a global land use model to account for these punctualities and intending to answer the following research questions:

1. How would Brazilian LUC dynamics evolve over this century under diverse biophysical and socioeconomic pathways?
2. Does achieving the deforestation reduction target for Legal Amazon and Cerrado lead to agricultural relocation and leakage effects in Brazil and other countries?

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<sup>1</sup> Legal Amazon is a political delimitation that includes the whole Amazon biome and parts of Cerrado (Brazilian savannah) and Pantanal (wetlands). Figure 3 in section 2.3.3 presents Legal Amazon area.

## **1.2. Thesis structure**

The thesis has the following structure: In section 1.3, I discuss agriculture and deforestation and I present definitions of important terms. In section 1.4, I historically contextualize land-use dynamics in Brazil, present political instruments for avoiding deforestation and present diverse approaches for assessing such issues. In section 2, I present the global land-use model used for the present research and its specific settings for addressing the research questions. In section 3.1, I present the results and discussions related to the research question number 1 and in section 3.2, related to the research question number 2. Lastly, in section 4, I present the conclusions.

### **1.3. Land-use change dynamics**

#### **1.3.1. Agriculture and deforestation**

Historically, humans have modified the landscapes for fulfilling food demand, for reducing exposure to natural variability of food supplies and for enhancing human welfare (KAREIVA et al., 2007). Agricultural land has been expanding over other natural land since agriculture has suppressed hunt as a way of living (KAREIVA et al., 2007). More recently, the growing population with higher food demands required even more agricultural production, which has been met by both extensification (FOLEY, 2005) and intensification (RAY et al., 2013). In 2016, 37.4% of the terrestrial surface was under agricultural use, either as cropland or pastureland (FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS (FAO), 2019). Agricultural production will need to keep increasing to guarantee food provision for a considerable high global demand (TILMAN et al., 2011). Closing the yield gaps (GODFRAY et al., 2010) and promoting a sustainable intensification (THE ROYAL SOCIETY, 2009) have been highlighted as potential solutions. However, crop yield has been increasing at lower rates than required to meet future demand (RAY et al., 2013).

While intensification is not enough to fulfill the demand, extensification will remain as an alternative and extensification over forestland is a major concern. Tropical forests were the main sources of new agricultural land in the 1980s and 1990s (GIBBS et al., 2010). Those forests account for 31 percent of ice-free land cover (BOUCHER et al., 2011) and harbor more than half of all known plant species (MAYAUX et al., 2005). Its total Carbon content has been estimated at 638 Gt for 2005, which is more than stored in the entire atmosphere (UNITED NATIONS FRAMEWORK CONVENTION ON CLIMATE CHANGE (UNFCCC), 2011). Its related activities are strategic for providing ecosystem services and goods (STRAND et al., 2018), including driving local climate by modulating energy and water fluxes (ALKAMA; CESCATTI, 2016). Until now, agriculture extensification used the planet's resources, overlapped forests, and undermined the capacity of ecosystems to sustain food production (FOLEY, 2005).

Land-use change dynamics in tropical regions also raise environmental concerns due to the usual competing interests between forest conservation and agriculture. Developing countries are often located in tropical areas and base their economy in agricultural related activities. The dependence on extracting natural resources and agricultural activities is a regular step towards high development that currently developed countries have passed through centuries ago. Such activities are closely related to deforestation, the act of converting forestland to non-forestland or degradation of

forestland quality (FAO, 2007). The occupancy of forests has usually two different moments: At first, the governments encourage people and industry by developing infrastructure and offering cheap land; in the second moment, when land is already occupied, the expansion becomes more “enterprise-driven” (RUDEL, 2007).

Demand will increase in the next decades (TILMAN et al., 2011) enhancing the enterprise-driven LUC. Population and income growth will lead to a high increase in global food production and up to 14% increase in agricultural land from 2010 to 2030 (SCHNEIDER et al., 2011). Over this century, food and feed crops would expand more than 400 million ha and pastureland more than 250 million ha, depending on how the socioeconomic features evolve over time (POPP et al., 2017). Poor governance and short terms economic targets combined with high increases in global demand for agricultural commodities contribute for the maintenance of extensive agriculture and deforestation as part of the agricultural land-use dynamics (BOUCHER et al., 2011). Around 130 million ha of forest were converted to non-forestland or lost through natural causes from 2000 to 2010 (FAO, 2010). Diverse measures shall be applied in order to mitigate deforestation or even to drive it to specific areas and, at the same time, assure agricultural production and food security. Otherwise, while the value of environmental goods and services are not part of the production function, deforestation will remain as the optimal solution to fulfill global food demand.

Developing countries have been called to reduce their Greenhouse Gas (GHG) emission (UNFCCC, 1998) and land use sector can be promising for it. In those countries, in general, the services sector barely contributes to GHG emissions and the industry is incipient. Therefore, the Agriculture, Forestry and Other Land Use (AFOLU) sector became the one to be dedicated in order to reduce emissions by avoiding deforestation and enhancing afforestation. Especially for the land abundant countries with extensive and low technology agriculture, there was a huge GHG emission reduction potential at a low marginal abatement cost (MCKINSEY & COMPANY, 2013). In addition, REDD+ can provide financial rewards to developing countries for their GHG emission reduction, increasing the economic feasibility of reducing deforestation. A developing country would invest in reducing deforestation and afterward sell its reduction on GHG emissions to developed countries so they can achieve their own GHG reduction targets (PHELPS; WEBB; AGRAWAL, 2010). Besides this production point of view, the demand side may require environmental friendly products as part of social and moral values (MAZAR; ZHONG, 2010) and some consumers are more likely to purchase products not related to deforestation. Moreover, in the last decades, global warming

impacted annual economic growth by accumulating substantial declines in economic output in hotter, poorer countries and increases in many cooler, wealthier countries (DIFFENBAUGH; BURKE, 2019). From this perspective, especially for poorer countries, reducing climate warming can result in economic advantages.

Incentives from the demand and production sides exist, reduced climate warming can benefit developing countries, and international community pressures national agents for adopting mitigation acts. In this context, some developing countries have committed to reducing deforestation rates intended to minimize impacts of climate change as part of their Nationally Determined Contributions (NDC). Such commitments drive their own national land use and impact global land use by interconnected markets that relocate agricultural activities and leakage effects. Mitigation measures such as oversights, creating protected areas (PAs) and afforestation are likely to promote desired mitigation outputs in the site they are applied, driving national land use in a more environmentally sustainable way. However, the same measures may lead to undesired international impacts, such as increasing deforestation elsewhere. The impacts of mitigation measures should be evaluated in a global-temporal perspective (MEYFROIDT et al., 2013) in order to avoid potential undesired effects and to enhance measures with benefits beyond its original aims. For doing so, some concepts are discussed in the next section in order to understand the dynamics related to national land use policy and its national and international impacts.

### **1.3.2. Impacts of mitigation**

The evaluation of measures intended to reduce deforestation and to incentivize agriculture must consider complex interactions accounting for geographical and temporal side-effects (HENDERS; OSTWALD, 2014; MEYFROIDT et al., 2013). These interactions promote other outcomes besides the original aim of the mitigation policies that may oppose or enhance it. In the present research, the policy outcomes are discussed from the perspective of mitigation and adaptation, and the interactions between policies are discussed from the perspective of co-benefits and adverse side effects.

**Mitigation** is an anticipatory (e.g. avoiding deforestation) or proactive (e.g. afforestation) measure intended to avoid potential future environmental condition (BIESBROEK; SWART; VAN DER KNAAP, 2009). More specifically, **mitigation** of climate change is “a human intervention to reduce the sources or enhance the sinks of greenhouse gases” (ALLWOOD et al., 2014, p. 1266). Such interventions include avoiding deforestation and enhancing afforestation in order to promote the outcome of

reducing or avoiding GHG emissions. Reducing deforestation contributes to the maintenance of the forest stock. Companies are aware that their association to deforestation reduce profits (CARBON DISCLOSURE PROJECT, 2017) and the value of forests' goods and services can be estimated (STRAND et al., 2018). The reduction of global GHG emissions, by its turn, is a step required to hold the increase in the global average temperature below 2°C above preindustrial levels (UNFCCC, 2015). Reducing deforestation and increasing afforestation enhances the reduction of GHG emissions as well. Though, the effects of GHG mitigation are only effective if the mitigation action that promoted it is taken over very long time periods (BIESBROEK; SWART; VAN DER KNAAP, 2009). Moreover, the distribution of its benefits is uncertain (in geographical and temporal perspectives) as they are public goods, which implies the issue of free riders.

**Adaptation** is “the process of adjustment to actual or expected climate and its effects” (ALLWOOD et al., 2014, p. 1251) in order to “moderate or avoid harm or exploit beneficial opportunities” (ALLWOOD et al., 2014, p. 1251). By one side, adaptation measures can be short-term investments to promote short-term outcomes (GOKLANY, 2007) and have been predominantly reactive to the current environmental condition (BIESBROEK; SWART; VAN DER KNAAP, 2009), such as emergency response and disaster recovery (SPERLING; SZEKELY, 2005). On the other side, it can also be long-term investments to promote long-term outcomes such as current technological change investments to increase future yields and enhance food security (Intergovernmental Panel on Climate Change (IPCC), 2007). Higher yields enable higher production without agriculture land expansion and prevent potential decreases in production due to climate change or climate variability. Decreasing the share of expenditure on food enhances food security, both by increasing income or by decreasing food prices. Higher yields enhance food security as well, as it helps to prevent decreases in food production. Adaptation is largely space dependent and requires tailor-made policies, positioning it in the broader context of the socio-economic process (BIESBROEK; SWART; VAN DER KNAAP, 2009). In addition, more mitigation in the present would imply less adaptation required in the future (BIESBROEK; SWART; VAN DER KNAAP, 2009) and this has been demonstrated for the Brazilian hydropower sector (LUCENA et al., 2018).

The interactions between policies, including mitigation and adaptation measures, may promote other positive or negative effects from the environmental perspective. The IPCC defines as **co-benefits** “the positive effects that a policy or measure aimed at one objective might have on other objectives, without yet evaluating

the net effect on overall social welfare” (ALLWOOD et al., 2014, p. 1257). Therefore, it is a co-benefit when a mitigation of deforestation policy has positive (or desired) effects on the outcomes of adaptation measures (e.g. increase yields and enhance food security). Such dynamic strengthen the overall effectiveness of environmental policies. For example, if besides GHG removal, afforestation promotes microclimate management and improve the ecosystem resilience to climate variability, then the policy aimed to mitigation has a co-benefit to adaptation. From the perspective of the environment, it is also a co-benefit if the government creates PAs to reduce deforestation and the producers decide to invest in technology to increase yields and production once there is less available land to expand.

The IPCC defines as **adverse side effects** “the negative effects that a policy or measure aimed at one objective might have on other objectives, without yet evaluating the net effect on overall social welfare” (ALLWOOD et al., 2014, p. 1251). Therefore, it is an adverse side effect when a mitigation of deforestation policy has negative (or undesired) effects on the outcomes of adaptation measures (e.g. decrease yields and diminish food security). Such dynamic weakens the overall effectiveness of environmental policies. For example, an afforestation policy designed to remove GHG made by a high water demanding plantation can reduce local water availability, and then the policy aimed to mitigation has an adverse side effect to adaptation. Another example: it is an adverse side effect if the government creates PAs to avoid deforestation and it drives agricultural land to less productive areas, implying higher production costs and higher food prices.

**Leakage** is a specific kind of adverse side effect that refers to a relocation of the environmental impact that counteracts the intended effects of the initial policy (MEYFROIDT et al., 2013). It is also used in a context where the “reduction in emissions (relative to a baseline) in a jurisdiction/sector associated with the implementation of mitigation policy is offset to some degree by an increase outside the jurisdiction/sector [...]” (ALLWOOD et al., 2014, p. 1265). Consider an area  $x$  which belongs to a bigger area  $y$  ( $x \subset y$ ). Hypothetical mitigation of deforestation measure (e.g. PAs) applied in  $x$  intends to promote the mitigation outcome of avoiding deforestation (or reducing GHG emissions) in  $x$ . However, because of interconnected markets and displacement effects of the agricultural activities (MEYFROIDT et al., 2013), the mitigation of deforestation measure applied in  $x$ , intended to reduce deforestation in  $x$ , may also increase deforestation in  $y$ , which in an overall perspective counteract the indented outcome in  $x$  (MOILANEN; LAITILA, 2016). The leakage effect occurs when there is a negative

mitigation outcome in y as a result from a mitigation measure applied in x, both assessed with the same variable (e.g. deforestation in x and deforestation in y). It is deforestation leakage when a mitigation measure reduces deforestation in x but increases it in y (AUKLAND; COSTA; BROWN, 2003; MEYFROIDT et al., 2013). It is emissions leakage when the mitigation measure reduces GHG emissions in x but increases it in y (ALLWOOD et al., 2014; HENDERS; OSTWALD, 2012). Deforestation leakage and emission leakage correlates closely because deforestation is an important source of Carbon dioxide (CO<sub>2</sub>) emissions. The presence of leakage does not imply a complete offset of the overall policy outcome. There can be a leakage in small scale and the overall effect of the policy still be positive, even though with leakage effect.

In the leakage concept, the increased deforestation (or increased GHG emissions) in y occurs due to relocation or displacement of agricultural land (cropland and pastureland) from x towards forestland in y (HENDERS; OSTWALD, 2012). This relocation is driven by diverse other factors such as biophysical conditions, distance, infrastructure, governance, trade agreements, and others. By nationally protecting forests, interconnected markets may displace land use and promote deforestation abroad (LAMBIN; MEYFROIDT, 2011; MEYFROIDT et al., 2013). The reduced supply of goods and services in x would shift the production and the market equilibrium to y (HENDERS; OSTWALD, 2012). Such behavior is due to the demand for products related to deforestation. For example, a hypothetical policy creates PAs and makes unfeasible potential cropland expansion to those areas. Assuming that cropland demand will be fulfilled anyhow, then the displacement of production will only be a matter of time and place. If the displacement of production occurs by clearing forestland, there is deforestation leakage effect. Besides the agricultural land relocation, the mitigation policy may determine changes in production and trade (ALLWOOD et al., 2014). Such impacts do not directly imply positive or negative statements and are not co-benefits neither adverse side effects.

One way of preventing leakage is by promoting global policies: the mitigation measure applied to y (e.g. world) instead of x (e.g. a country). A hypothetical global regulation consists of Carbon emission prices, which has been demonstrated as an efficient way to globally mitigate GHG emissions (POPP et al., 2017). Besides carbon prices, international cooperation towards national mandatory regulations, such as limiting deforestation, would enhance global GHG mitigation while minimizing leakage (IPCC, 2007). Without global regulation, leakage becomes an inevitable result of economically driven deforestation (BOUCHER et al., 2011). In this case, the focus should

be on minimizing and guiding leakage to places where it does the least environmental and social damage. From the GHG emissions perspective, even though the agricultural conversion of non-forested areas can release a considerable amount of CO<sub>2</sub> (POPP et al., 2014), it is still preferable to drive leakage to non-forested areas than to forestland.

## **1.4. Land-use Dynamics in Brazil**

### **1.4.1. Historical contextualization of Brazilian agriculture**

Brazil has a large-scale agricultural system that has been characterized by massive governmental intervention (CHADDAD et al., 2006) and satisfactory environmental conditions (EMBRAPA, 2018). The suitability for agriculture and the imperial interests drove the Brazilian economy towards agriculture since the country was a colony. Coffee was the main agricultural commodity by the end of the 19<sup>th</sup> century and beginning of the 20<sup>th</sup> (MAPA, 2018). During that time, the government invested in infrastructure for production and transport (MAPA, 2018; NICHOLLS, 1970) and began an interventional interpose that included government purchases and storage of excess supply (CHADDAD et al., 2006).

From the beginning of the 1930s, the coffee industry declined and the country experienced a low productivity agricultural sector until the 1960s (NICHOLLS, 1970). Policies to modernize agriculture were limited to coffee, cotton and sugar cane by organizations of the São Paulo state government, but with minor national impacts (PASTORE; DA SILVA DIAS; DE CASTRO, 1976). The small farms to support domestic demand prevailed in the country, especially in the South (SCHALLENBERGER; SCHNEIDER, 2010). The agricultural land expanded in the South and Southeast, mainly in the states of São Paulo and Paraná (NICHOLLS, 1970).

National wide scientific researches towards higher yields agriculture started in the 1960s and reflected in soybean increased yields in the 1970s (PASTORE; DA SILVA DIAS; DE CASTRO, 1976). The governmental interventional approach remained until the 1980s (CHADDAD et al., 2006; MARTINELLI et al., 2010) but, only at minor relative scale due to the debt crises (CHADDAD et al., 2006). Although this was a troubling moment, from 1975 to 1998 the agriculture total-factor productivity (TFP) has almost doubled (GASQUES; BACCHI; BASTOS, 2018; MUELLER; MUELLER, 2016). Agriculture land expanded towards Center-West, mainly into Mato Grosso state, and also towards Amazon Forest and Cerrado (SCHALLENBERGER; SCHNEIDER, 2010). From 1970 onwards, cattle ranching predominated in Amazon, accounting for 70% of clearing activities (FEARNISIDE, 2005).

In 1994, after Brazil's macroeconomic stabilization that came up with Plano Real (the implementation of the Brazilian currency), the national agribusiness started its "enterprise driven" phase, the second agricultural development moment described by Rudel (2007). The expansion of the international demand for agricultural commodities lead to a long period growing commodity prices (MUELLER; MUELLER, 2016), which supported a more exportation driven production. Brazilian exports were boosted due to the nearly 35% drop in the value of the Brazilian Real in 1999, when the country started to operate under a floating exchange rate regime, a phenomenon known as Samba Effect (HOLZ, 2000). In addition, soybean, maize, and sugar cane yields increased until 2012 and cattle stocking rate per hectare increased (DIAS et al., 2016). The agricultural land consolidated its expansion in Mato Grosso state and southern Amazon (IORIS, 2018). From 1990 to 2010, area for cattle ranching in Amazon increased more than 50% while it decreased in other regions (DIAS et al., 2016), indicating that despite overall intensification pastureland remains driving deforestation in Amazon.

Increasing international demand and agricultural yields, as well as the depreciation of Brazilian Real, enabled the country to become one of the global major crop and livestock products exporters from the 2000s onwards (EMBRAPA, 2018; MUELLER; MUELLER, 2016). Brazil increased its agricultural TFP 60% from 1999 to 2015 (GASQUES; BACCHI; BASTOS, 2018). The country also became one of the global technological leaders in soybean production (EMBRAPA, 2018). Clear evidence of livestock intensification was -found in Cerrado, Center-West, South, and Southeast regions and MATOPIBA<sup>2</sup> in the last decades (DIAS et al., 2016). The country is one of the top five producers of coffee, soybean, orange, beef, and corn (ANDERSSON; AXELSSON, 2016).

In one century, Brazil moved from technologically outdated agriculture to catch up top world's producers (ANDERSSON; AXELSSON, 2016). Some of the key features for this were the economically disciplined institutional setting, government intervention on market failures instead of massive intervention and good macroeconomic conditions (MUELLER; MUELLER, 2016), besides the availability of natural resources and R&D investments (EMBRAPA, 2018). Brazil's agricultural land has reached its maximum area in the 1980s (DIAS et al., 2016). However, it keeps expanding due to abandonment or conversion to nonagricultural land. As an overview, since the 1980s,

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<sup>2</sup> MATOPIBA is acronym for an area that includes parts of the following states: Mato Grosso, Tocantins, Piauí and Bahia. Figure 3 in section 2.3.3 presents MATOPIBA area.

agricultural expansion occurred towards Center-West and North and, more recently, to MATOPIBA (BRAGANÇA, 2018; DIAS et al., 2016).

#### **1.4.2. Deforestation policies for Legal Amazon and Cerrado**

The success of Brazilian agriculture has been associated with widespread ecosystems depletion, especially the Cerrado and the Amazon rainforest (MARTINELLI et al., 2010) and the Atlantic Forest (RIBEIRO et al., 2009). Deforestation in Brazil started by cropland and pastureland expansion over the coast during the colonial period taking over Atlantic Forest. Most of the cities and population have settled around the coast, pressuring even more for deforestation. Even though the Atlantic Forest is recovering in the last years (MOLIN et al., 2017), its current estimated area is between 11.4% and 16% of its original land, most of it distributed in isolated fragments of forest (RIBEIRO et al., 2009). The Cerrado biome is less dense in its biomass, but aggregates good conditions for pasture and crop farming (BRASIL, 2016), leading to high depletion of its area (HARFUCH; MOREIRA, 2012). It faces a rapid process of land conversion to soybean and maize plantation, cattle raising (KLINK; MACHADO, 2005) and an imminent expansion of sugar cane plantation (CARVALHO; DE MARCO; FERREIRA, 2009). The biome covers 2 million Km<sup>2</sup> (25% of Brazilian area) and half of it has already been replaced by cropland or pastureland (CARVALHO; DE MARCO; FERREIRA, 2009). Deforestation in Legal Amazon, which comprises the whole Amazon biome, reached 27,800 Km<sup>2</sup> in 2004 and reduced to 7,900 Km<sup>2</sup> in 2018 (INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS (INPE), 2018). Amazon biome covers around 4 million Km<sup>2</sup> (50% of Brazilian area) of which 82.8% remains as forestland 11.6% as agricultural land (MAPBIOMAS, 2019).

Although deforestation has been part of Brazilian land-use dynamics, environmental concern has also taken a part in the agricultural planning in the recent decades (BRASIL, 2009b, a, 2010, 2012, 2018; BRAZIL, 2015; MARTINELLI; FILOSO, 2009). Some Brazilian recent policies account both for environment and agriculture in order to enable socioeconomic development and environmental preservation (MARTINELLI; FILOSO, 2009). The main of these policies is the National Policy on Climate Change (NPCC) (BRASIL, 2009a, 2018b) that regulates all other Brazilian actions on climate change, including Brazil's NDC. NPCC's general objective is to harmonize socioeconomic development and protection of the climate system by reducing anthropogenic emissions and strengthening GHG removals (BRASIL, 2009a). NPCC establishes Sectorial Plans with diverse measures to support achieving Brazilian

NDC and other mitigation commitments. There are specific Sectorial Plans for Legal Amazon and Cerrado, described in the following.

One of these Sectorial Plans is the Action Plan to Prevent and Control Deforestation in the Legal Amazon (Plano de Ação para Prevenção e Controle do Desmatamento na Amazônia Legal - PPCDAm) (BRASIL, 2018a). It dates from 2004 and design policies and actions regarding the perseverance of Legal Amazon, an area larger than the Amazon Biome that includes part of Cerrado (Brazilian Savannah) and part of Pantanal (wetlands). One of its objectives is to reduce annual deforestation in the Legal Amazon by 80 percent until 2020, using the average deforestation between 1996 and 2005 as a basis. Diverse actions on oversight, monitoring, and enhancing sustainable activities have been taken in order to achieve this target. From 2004 to 2012 deforestation in Amazon have continuously decreased (BRASIL, 2018a). The establishment of PAs, the Soy Moratorium<sup>3</sup> and the synergistic actions between satellite monitoring and oversights were the main drivers to reduce deforestation (BRASIL, 2018a). PAs were created in areas of intense land conflict, next to the borders of the agricultural frontier in order to avoid deforestation to go further deep in the Amazon Forest (SOARES-FILHO et al., 2010). Even aside from the specific actions of the PPCDAm, the Soy Moratorium, signed in 2006, may have contributed to the result because it had an inhibiting effect on the expansion of the soybean border in the Amazon Biome (RUDORFF et al., 2011). Meanwhile, the Real-time Deforestation Detection project (DETER), which actually captures near-real-time deforested areas from satellite images, had its data linked to the oversight planning action (BRASIL, 2016). The synergic data flow from DETER to support oversight actions only began in 2004, being the main innovation of the PPCDAm (BRASIL, 2004). DETER reports any deforestation site of at least 25 ha and the quick oversight intervention are determinants for the reduction on deforestation rates (BRASIL, 2018a). Annual deforestation rate decreased from 27,800 Km<sup>2</sup>, in 2004, to 4,600 Km<sup>2</sup> in 2012 (INPE, 2018).

Although the success of PPCDAm in reducing deforestation has been recognized (GREENPEACE, 2013; SOARES-FILHO; RAJÃO, 2018), since 2012 the annual deforestation rate is increasing again (INPE, 2018). By 2013 it was already known that one of the challenges of the DETER system to further reduce deforestation would be to identify areas smaller than 25 ha (BRASIL, 2013). In 2001, 29% of the deforested areas

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<sup>3</sup> The Soy Moratorium is an agreement between the representatives of soy producers, environmental NGOs and the Brazilian government that soybean could not be produced in deforested areas in the Amazon biome.

were less than 50 ha and, in 2015, 62% were less than it (MOUTINHO; GUERRA; AZEVEDO-RAMOS, 2016), evidencing that deforesters are adapting to the oversight system. In 2015, a new methodology (DETER-B) capable of identifying near-real-time deforestation of up to 1 ha was presented (DINIZ et al., 2015) and is now used to support oversight actions. In addition, in 2012, the new Brazilian Forest Code<sup>4</sup> (BRASIL, 2012a) was implemented and preliminary analysis concluded that it could potentially change the reduction dynamics observed until then (GREENPEACE, 2013). The new Forest Code qualified 90 percent of the Brazilian rural properties for amnesty regarding the non-compliance with the old Forest Code (SOARES-FILHO et al., 2014). The strict enforcement of the Forest Code would preserve Brazilian forests (SOTERRONI et al., 2018a) and DETER-B should enhance the effectiveness of oversight actions, but deforestation in Legal Amazon increased 72% since 2012 (INPE, 2018). PAs increased by 64% from 2000 to 2011, and then increased only 2.2% from 2011 to 2017 (SOARES-FILHO; RAJÃO, 2018). PAs are the main mitigation measure in Amazon biome and its stagnation is correlated to the recent increase in deforestation (SOARES-FILHO; RAJÃO, 2018).

Another Sectorial Plan of Brazil's NPCC is the Action Plan to Prevent and Control Deforestation and Fire in the Cerrado (Plano de Ação para Prevenção e Controle do Desmatamento e das Queimadas no Cerrado – PPCerrado) (BRASIL, 2016). It dates from 2010 and design policies and actions regarding the preservation of the Cerrado Biome. One of its objectives is to reduce annual deforestation in Cerrado by 40 percent until 2020, using the average deforestation between 1998 and 2008 as a basis. Similarly to PPCDam, the oversight, monitoring and enhancing sustainable activities were the strategies defined to achieve the target. Although unlike for the Legal Amazon, there is no near-real-time deforestation monitoring for Cerrado. By the time PPCerrado was released, the annual deforestation rate there was already below the target value one year before, what demonstrated an uncoordinated approach among different governmental sectors (GREENPEACE, 2013). As the target was already achieved, only less than one-third of the planned actions were actually implemented in the initial years (GREENPEACE, 2013). There is a lack of deforestation data for Cerrado that makes it difficult to analyze PPCerrado results. The deforestation monitoring in Cerrado begun in 2009 (data from 1998 to 2008 to define the reduction targets are estimates, not observed

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<sup>4</sup> The New Forest Code is Brazilian law from 2012 that provides for the protection of all Brazilian native vegetation. The law, however, is controversial because it can potentially increase deforestation (SOARES-FILHO et al., 2014).

data) and, more recently, national data were available for the period between 1990 and 2012 (DIAS et al., 2016).

Amazon and Cerrado compress the current deforestation frontiers in Brazil and are determinant for both agricultural production and forest conservation. Policies such as PPCDAm and PPCerrado may affect Brazilian and global land-use dynamics (as discussed in Section 1.2.3). Moreover, these policies are part of the Brazilian NPCC and they support the achievement of Brazil's NDC mitigation commitment. As discussed in section 1.3.2, such policies can determine Brazilian land-use dynamics and affect international LUC as well. The understanding of future Brazilian LUC depends on researches carried at the local scale, to overcome more practical and specific issues, and at the global scale, to design the best national policy setup that contributes to global objectives. In the following section, I present both kind studies that assess Brazilian LUC and the impacts of mitigation, at regional, national and global scales.

#### **1.4.3. Assessing land use and leakage**

The assessments of land-use dynamics include regional/national and national/global setups, each of them with their focus and strengths. At the local or national scales, the interface DINAMICA EGO (SOARES-FILHO et al., 2004; SOARES-FILHO; CERQUEIRA; PENNACHIN, 2002) is a common platform for studying land use and leakage. This framework supports the development of multi-region and multi-scale geomodeling applications, depending on the input maps and datasets (FERREIRA; SOARES-FILHO; PEREIRA, 2019). The platform has been applied to evaluate deforestation effects coming from the construction of roads in the Amazon and Rondônia states (DOS SANTOS JUNIOR et al., 2018). Results demonstrated increasing deforestation around the roads in the coming decades and the authors suggest that oversight actions and PAs around the roads would minimize its negative environmental impacts (DOS SANTOS JUNIOR et al., 2018). DINAMICA EGO was one of the methodological components to estimate the cost of ending deforestation in Amazon (NEPSTAD et al., 2009). The authors estimated a cost between 6.5 to 18 billion US\$ to stop deforestation before it reaches 20% of forest's original area before 2020, which would be an extremely difficult achievement (NEPSTAD et al., 2009). DINAMICA EGO was also applied to evaluate the loss and recovery of Atlantic Forest (MOLIN et al., 2017). The authors concluded that by one side, the forest is regrowing at a small pace, but on the other side, there are persistent ecosystem service losses, due to continuous trends of older forest loss (MOLIN et al., 2017).

Regarding national wide researches, the Brazilian Land Use Model (BLUM) (ICONE, 2012; NASSAR et al., 2011) has been used alone and in combination to other methods, contributing especially to the agricultural demand projections. BLUM is a one-country model, with six regions, multi-market, dynamic, partial equilibrium economic model that accounts for supply and demand and project outputs up to 20 years forward (NASSAR et al., 2011). Although the model has gridded input data, its outputs are only at the six region scale which makes it impossible to assess the impacts spatially (NASSAR et al., 2011). Harfuch and Moreira (2012) used BLUM to demonstrate that the creation of PAs in Cerrado promotes deforestation leakage effect to other biomes, especially the Amazon region, besides increasing commodities prices and decreasing production. The authors argue that it would be rational to have agricultural expansion in Cerrado instead of Amazon and Atlantic Forest in order to reduce emission from LUC. More recently, Harfuch et al. (2016) incorporated different levels of livestock productivity into BLUM and demonstrated that migration from lower to higher technologies will continue in the future, indicating an intensification trend in the sector.

Some features from DINAMICA EGO and from BLUM are also part of another modeling tool, the SimBrasil/OTIMIZAGRO (SOARES-FILHO et al., 2012; SOARES-FILHO et al., 2013). This is a nationwide spatially explicit model built on DINAMICA EGO interface. It simulates land-use dynamics under diverse scenarios of agricultural land demand calculated by BLUM, including a traditional agricultural expansion as a reference scenario and a low carbon agriculture implementation scenario (GOUVELLO et al., 2010). SimBrasil/OTIMIZAGRO has been used to evaluate the implications of the Brazilian Forest Code (SOARES-FILHO et al., 2016). The research demonstrates that Brazil would hold the largest market for trading forests in the world due to the new Forest Code, if all the available supply were offered (SOARES-FILHO et al., 2016). Rochedo et al. (2018) used SimBrasil/OTIMIZAGRO interface to evaluate diverse levels of environmental governance to control deforestation in Brazil. The authors concluded that it is infeasible for the country to meet its own international commitments to GHG emission reduction without the current deforestation control policies (ROCHEDO et al., 2018).

The methods and studies previously mentioned in this section disregard to the international effects that also drive Brazilian internal land-use dynamics, such as global demand and climate change effects. For researches on the local/regional scale, the usage of LANDSHIFT (SCHALDACH et al., 2011; SCHALDACH; KOCH, 2009) enables an integrated approach between global dynamics and field measurements. LANDSHIFT

represents land-use change using macro-level parameters such as population and environmental policy and micro levels input such as conservation areas and population density to produce time-series grid maps (SCHALDACH et al., 2011). Recently, a series of studies in southern Amazon using LANDSHIFT discussed LUC. Projected LUC from 2010 to 2030 in the region depends largely on the dynamics between agricultural production and intensification (SCHALDACH et al., 2018), besides global and regional demand (GÖPEL et al., 2018). Moreover, important dynamics to determine deforestation have been observed at the sub-regional scale (GOLLNOW et al., 2018) and well-defined land tenure policies have been implemented as a potential solution (BENATTI; DA CUNHA FISCHER, 2018).

LANDSHIFT enables global impacts to be assessed at local/regional scales, however still do not account for local/regional policies affecting global dynamics. Global land-use models overcome such limitation by simulating the land-use sector at a global and temporal perspective while preserving some important national/regional features. This class of global models accounts for international trade, diverse drivers of LUC, at regional and grid scales, and may consider socioeconomic (population, income, diet, etc.) and biophysical (CO<sub>2</sub> fertilization, climate change, yields, carbon stocks, etc.) scenarios for deriving specific related outputs. However, in order to account to a broad set of interactions, they oversimplify some process by taking advantage of some underlying assumptions.

The following global land-use models have been used to study Brazilian land-use dynamics: IMAGE (ALCAMO, 1994; ROTMANS, 1990; STEHFEST et al., 2014), GCAM (BRENKERT et al., 2003; KYLE et al., 2011; WISE et al., 2014), GLOBIOM (CAMARA et al., 2015; HAVLÍK et al., 2011; SCHNEIDER et al., 2011) and MAgPIE (DIETRICH et al., 2019; LOTZE-CAMPEN et al., 2008)<sup>5</sup>. The most recent version of all the above-mentioned models have or may have Brazil as a single region in their setup, which increases the reliability of Brazilian dynamics representation. Therefore, all of them are able to account for international drivers into the Brazilian land-use dynamics as well as international leakage effects from Brazilian policies. However, the models differ largely on the Brazilian representation, on the usage of the models to address Brazilian

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<sup>5</sup> Models IMAGE and GCAM are also defined as Integrated Assessment Models (IAMs). IAMs aggregate even more characteristics than global land-use models, such as detailed representation of the energy and vegetation systems. The models MAgPIE and GLOBIOM have specific versions coupled to other models that are defined as IAMs as well: REMIND-MAgPIE and MESSAGE-GLOBIOM. From all of the studies presented in present research, only POPP et al. (2017) uses MAgPIE and GLOBIOM in their IAMs versions.

specific research questions and on the presentation/analysis of Brazilian outputs. In the following, I briefly describe those models' general features and their most relevant applications for Brazil.

IMAGE combines regional agro-economic, energy and climate policy modeling with land use, vegetation and hydrological modeling (DOELMAN et al., 2018). Doelman et al., (2018) projected global maps using IMAGE from 2010 to 2100 and briefly discussed some results for Brazil. The authors affirmed that, under low socioeconomic and biophysical pressure, there would be agricultural land abandonment in the Northeast of Brazil. Moreover, if we follow the path related to 1.5°C warming, there would be an abandonment of agricultural land also in the Southeast and South of Brazil. Another study used IMAGE to assess agricultural practices and N-fixation in Brazil (SMALING et al., 2008). The results demonstrate co-benefits between agricultural good practices and mitigation of GHG emissions, as in the mid-2000s the Nitrogen balance was positive in the Brazilian soybean chain (more N storage than released) (SMALING et al., 2008). Herreras Martínez et al. (2015) used IMAGE to assess the energy and emissions trends in Brazil up to 2050. Results demonstrate that deep CO<sub>2</sub> emissions reductions from the Brazilian side are required to meet its international commitments.

GCAM is a long-term, globally integrated model of human and physical earth systems (WISE et al., 2014). Its most recent version aimed to increase the physical detail and spatial resolution while preserving previous economic features of the model (WISE et al., 2014). Lucena et al. (2018) used the model to investigate interactions between climate change mitigation and adaptation in Brazilian hydropower sector. Results demonstrate that mitigation efforts at the present date could promote more diverse and less carbon-intensive adaptation technological options for the sector, which is a co-benefit from mitigation measures towards adaptation outputs.

The scope of researches about Brazil from IMAGE and from GCAM is narrow and literature does not present specific projections of Brazilian land-use pathways in the models' related publications. On the other side, the partial equilibrium economic model GLOBIOM, which already had a publication discussing Brazil as a single region (COHN et al., 2014), has gone even deeper in Brazil's representation. A regionalized version of the model was released as GLOBIOM-Brazil (CAMARA et al., 2015) projecting Brazilian land from 2000 to 2050 in ten year time steps. In this regionalized version, there is improved livestock and cropland allocation based on national statistics,

some features of the Forest Code, the Soy and Cattle Moratorium<sup>6</sup> and other refinements (SOTERRONI et al., 2018b). The representation of the Forest Code is by implementing in the model some of its mitigation measures, which include Legal Reserve recovery, small farms amnesty, and environment reserve quotas, among others. Overall, the model posits increased detail on the Brazilian biophysical features and on the representation of mitigation measures. Model validation to Brazilian data has proven better for GLOBIOM-Brazil than for the original GLOBIOM (SOTERRONI et al., 2018b).

According to GLOBIOM-Brazil results, the full enforcement of the mitigation measures from the Forest Code would prevent a net loss of 53.4 million hectares of forest (SOTERRONI et al., 2018a). However, this solution for the model comes with a required increase in cattle productivity of 56% in the next four decades alongside with other improvements (SOTERRONI et al., 2018a). Camara et al. (2015) also evaluated the compliance of the Forest Code and observed that cropland expands and pastureland decreases in Brazil by 2050 with or without the compliance of it. However, assuming the full enforcement of the Forest Code implies less cropland expansion, more pastureland decrease and the conservation of about 60 million ha of forestland in 2050 compared to a non-Forest Code scenario (CAMARA et al., 2015). Soterroni; Ramos, et al. (2018) compared GLOBIOM with GLOBIOM-Brazil and observed diverse wheat trends for Europe, South Asia and the USA and also diverse soybean trends for Brazil, Rest of Latin America and the USA. Their findings attest for the importance of a good representation of the main agricultural global players in the global land-use models, as it can lead to project different crop production pathways. Zilli et al. (2018), by its turn, evaluated GLOBIOM-Brazil over one set of socioeconomic assumptions (business as usual) and two sets of biophysical assumptions (reference and mitigation). The median result between both biophysical sets of assumptions indicates that grassland area and production will decrease and that soybean area will decrease but its production will increase.

The last of the previously listed model is MAgPIE, which is an economic global partial equilibrium model for the agricultural sector that accounts for diverse sets of socioeconomic and biophysical assumptions. MAgPIE has been recognized as perhaps the first model to integrate gridded vegetation model to an economic land allocation approach, which allows for greater consistency between economic decisions and

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<sup>6</sup> Similarly to the Soy Moratorium, the Cattle Moratorium is an agreement between the representatives of cattle producers, environmental NGOs and the Brazilian government that cattle could not be produced in deforested areas in the Amazon biome.

biophysical characteristics (WISE et al., 2014). Although on its previous versions it had only Latin America as region, the combination of MAgPIE supply/demand and yields to regional models allowed some researches in the São Francisco River Basin, northeastern Brazil. Beck (2013) disaggregated MAgPIE and simulated land-use patterns in the basin, which was further used by Koch et al. (2015) to evaluate impacts of two socioeconomic future scenarios in cropland and water availability in the regions. Sugar cane plantations expands in both scenarios evaluated by Koch et al. (2015) from 2005 to 2035. Alcoforado de Moraes et al. (2018), by its turn, identified the highest current and future water values in municipalities with a significant proportion of area growing irrigated sugarcane. Their findings contribute to design policies that drive sugar cane expansion towards areas with high water availability or increase the water availability in the areas where sugar cane is expected to expand.

After these researches using MAgPIE in the São Francisco River Basin, the model evolved into a modeling framework that allows for multiregional settings (DIETRICH et al., 2019). The first application of this new feature was the development of MAgPIE-Brazil, which preserves all MAgPIE's features, but is built from the Brazilian-centric point of view, in which the country is a single region and uses higher definition biophysical data. The implementation of deforestation policies in MAgPIE-Brazil is by representing the achievement of the committed reductions in deforestation and increases in afforestation. Differently from GLOBIOM-Brazil, MAgPIE-Brazil uses the mitigation target as constraints to the model and not the mitigation measures itself (e.g. Legal Reserve recovery from the Forest Code). MAgPIE decides for the optimal mitigation measures to meet the mitigation targets. This implementation is globally consistent, as the mitigation targets relating to avoid deforestation and to afforestation of all countries were taken from the NDC documents and implemented in MAgPIE and MAgPIE-Brazil<sup>7</sup>. When comparing the outcomes regarding deforestation, MAgPIE-Brazil version behaves better than MAgPIE regarding the allocation of deforestation sites in Brazil and in Latin America (DIETRICH et al., 2019). Such results are the first insight that a regionalized version of the model is more suitable to assess regional dynamics of deforestation. Although MAgPIE-Brazil researches are still incipient, this is a first step towards enhancing its suitability to address local issues also driven by global dynamics.

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<sup>7</sup> NDC documents present information on current measures and targets as well as information on future measures and targets. The two kinds of information are dealt in MAgPIE and MAgPIE-Brazil. Section 2.3.3 presents further explanations on it.

As presented in this section, above-mentioned studies assess Brazilian land-use dynamics by regional, national or global scale methods. The regional ones may wisely address local issues but should not be extrapolated to elsewhere due to very singular regional features. In addition, they usually do not account for international drivers, such as global markets that drive leakage effects. The above-mentioned national scale methods may account for Brazil's dynamics well, especially the biophysical ones. However, they also lack including socioeconomic and international drivers into account. Global land-use models, by its turn, may overcome the previously mentioned limitations, as demonstrated by the recent researches using GLOBIOM-Brazil. In addition, the new MAgPIE modeling framework will allow for address national wide issues of specific countries from a global perspective, besides MAgPIE-Brazil. Finally, global land-use models may not be the best option for local scale issues. Global models usually take advantage of simplifying assumptions that present only minor effect at global scale. Notwithstanding, these assumptions might bias local scale outcomes.

There are several approaches for assessing land-use dynamics and leakage in the literature and each of them was built for different purposes. Having information provided by diverse methodological approaches enables to figure out their consonances, divergences and reduce uncertainties. Although the researches discussed in this section contribute for such aim, none of them have specifically addressed future Brazilian land-use pathways beyond 2050 neither evaluated the international impacts of avoiding deforestation in Brazil. Moreover, due to the uncertainties on which socioeconomic (RIAHI et al., 2017) and biophysical (VAN VUUREN et al., 2011) pathways the world will follow, modeling the full set of possibilities is required to cover a full range of possibilities. In the present research, I contribute to the diversity of approaches by using MAgPIE-Brazil to address the research questions raised in section 1.1. Analyzing land-use projections beyond 2050 and international impacts of Brazilian deforestation policies contributes to build knowledge for long-term Brazilian land-use policy.

## 2. MATERIAL AND METHODS

### 2.1. MAgPIE modeling framework

The complex relations between AFOLU sector and global environmental change requires methods able to account for such complexity, both from the biophysical and from socioeconomic perspectives. The Model of Agricultural Production and Its Impact on the Environment (MAgPIE) (LOTZE-CAMPEN et al., 2008) was first introduced as an attempt to simulate such relationships mainly focusing on crop production, land-use patterns and water use for irrigation. It is a partial equilibrium global model that minimizes a goal cost function through recursive dynamic optimization under the constraint of fulfilling an exogenous demand for food and other specific restrictions. Diverse regions interact through international trade; therefore, the regional and global demand can be fulfilled by the production of any region. The current version of the model is MAgPIE 4.0 Modeling Framework (DIETRICH et al., 2019) (henceforth MAgPIE), which is more detailed and flexible on its input data, more robust in its validation, and open source. It currently uses biophysical data inputs at 0.5 degree (approximately 55 by 55 km at the equator), it is able to use socioeconomic data at country level, endogenously simulate agricultural technological changes and its corresponding costs, accounts for livestock products, afforestation and mitigation of deforestation incentivized by Carbon emission prices, among other features.

Taking advantage of this framework, the present research contributed to the development of MAgPIE-Brazil (DIETRICH et al., 2019), a regionalized version of MAgPIE built from the Brazilian-centric perspective. It emphasizes data quality in Brazil and its main commercial partners and accounting for international related effects. In the next topics, I describe MAgPIE-Brazil's data preparation, its main settings and outputs related to the present research and I highlight its differences to MAgPIE. Besides

MAGPIE's description paper (DIETRICH et al., 2019), the model documentation with a detailed description of all model equations (DIETRICH et al., 2018a) and the model code (DIETRICH et al., 2018b) are available online.

## **2.2. Preprocessing of input data**

Preprocessing is preparing the input data in the format in which it is required by the model to run. It includes the corresponding spatial resolution and the level (from country to region) of socioeconomic data. Preprocessing allows focusing on specific areas, suiting for specific research questions and all the features that differentiate MAGPIE-Brazil from MAGPIE are set up at this point (before the model run). In the following sections, I describe these features and stress the differences and implications of each of them.

### **2.2.1. Grid level input data**

Biophysical and travel time input data has to be prepared in a grid resolution of 0.5°. These data include:

- a) yields of 19 crops<sup>8</sup> and pasture, both irrigated and rainfed, from 1995 to the last time step defined in the model run;
- b) carbon stocks in soil, litter, and vegetation, from 1995 to the last time step defined in the model run;
- c) water availability for 1995;
- d) water demand from 1995 to the last time step defined in the model run and;
- e) travel time to reach the closest city with 50.000 inhabitants, which is static over time.

The global vegetation and hydrology model Lund-Potsdam-Jena managed Land (LPJmL) (BONDEAU et al., 2007) provide the yields, carbon and water data to be used by MAGPIE. For providing it, LPJmL uses the climate model IPSL-CM5 Earth System Model in all the Representative Concentration Pathways (RCPs)<sup>9</sup> (VAN VUUREN et al., 2011). Travel time is taken from Nelson (2008) and the relative transport costs for each product are calibrated using total agricultural transport costs taken from the GTAP 7 database (NARAYANAN; WALMSLEY, 2008).

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<sup>8</sup>Soybean, maize, rice, sugar cane, sugar beet, rapeseed, groundnut, sunflower, palm oil, temperate cereals, tropical cereals, potato, cassava, pulses, cotton, fodder, bioenergy grains, bioenergy trees, others.

<sup>9</sup> I describe and discuss the RCPs usage in MAGPIE in Section 2.4.

### 2.2.2. Clusterization

Although grid level input data is available at  $0.5^\circ$ , it is necessary to aggregate the grid cells into clusters before running MAgPIE due to computational and feasibility requirements. The clusterization process (DIETRICH; POPP; LOTZE-CAMPEN, 2013) aggregates similar cells regarding yields, time travel, water availability and the MAgPIE regional setup (discussed in the next section). The preprocessing allows emphasizing specific areas to better address specific research questions. MAgPIE uses 200 clusters without explicitly weight to any area, whereas MAgPIE-Brazil uses 500 clusters, mainly focusing in Brazil and its commercial partners. By focusing in Brazil, it loses information in other areas, but this decision is in consonance with the research questions that are designed from the Brazilian perspective. Figure 1 presents the cluster distribution in MAgPIE default and Figure 2 presents the cluster distribution in MAgPIE-Brazil.

### 2.2.3. Socioeconomic input data and regional setup

Socioeconomic data includes population, income, food demand, diet composition, and others. Population and income are defined by the Socioeconomic Shared Pathways (SSPs)<sup>10</sup> (O'NEILL et al., 2017; RIAHI et al., 2017) and are exogenous to the model. MAgPIE uses 12 regions<sup>11</sup> defined to achieve better global consistency. It allows, however, for other regional setups, which are especially useful for addressing national wide issues of specific countries from a global perspective. Changing the regional setup affects socioeconomic data inputs accordingly. MAgPIE-Brazil uses 6 regions<sup>12</sup> focusing in Brazil and its commercial partners. Brazil (BRA), which is part of Latin America in MAgPIE, becomes a single region in MAgPIE-Brazil. The region Rest of Latin America (Latin America except Brazil) is defined as a single region because of its proximity to Brazil and its implications for deforestation. The main Brazilian commercial partners were defined by evaluating commercial flows of livestock-related products, soybean, and maize. They are the United States (USA), China (CHA) and Europe (EUR). All other regions aggregate socioeconomic data as one region named Rest of the World (ROW). The main disadvantage of having one big region as ROW is that this area is trade-free, which does not fit the reality. However, I assume that from the

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<sup>10</sup> I describe and discuss the SSPs usage in MAgPIE in Section 2.4.

<sup>11</sup> Canada, Australia & New Zealand (CAZ), China (CHA), European Union (EUR), India (IND), Japan (JPN), Latin America (LAM), Middle East and North Africa (MEA), Non-EU member states (NEU), Other Asia (OAS), Reforming countries (REF), Sub Saharan Africa (SSA), United States (USA).

<sup>12</sup> Brazil (BRA), Rest of Latin America (LAM), United States (USA), China (CHA), Europe (EUR) and Rest of the World (ROW).

Brazilian perspective, the dynamics in ROW are less relevant than in the other regions of MAgPIE-Brazil. Figure 1 presents the regional setup in MAgPIE and Figure 2, the regional setup in MAgPIE-Brazil.

The specific MAgPIE-Brazil settings for clusterization (Section 2.2.2) and for regional setup (Section 2.2.3) were defined in order to enhance the representation of Brazilian socioeconomic and biophysical dynamics, as well as the dynamics in some important regions related to the country. These settings define MAgPIE-Brazil and differentiate it from MAgPIE.

### **2.3. Model run – main features**

Each MAgPIE-Brazil run produces a series of archives containing the specific model settings, reference for its inputs, and output data. The validation documents (pdf files) present the outputs in a friendlier viewing than the other output archives, including all model's outputs, historical data, and its validation. The archives (AMBRÓSIO, 2019a) and the validation documents (AMBRÓSIO, 2019b) are available online. In order to address the research questions, I focus on the following model outputs: food and feed demand, natural land, CO2 emissions from LUC, agricultural land, production, yields, net-trade, and food price index.

The model operates in a modular setup, where specific modules execute specific calculations. The modular structure increases the transparency, the reproducibility and allows the comprehension of a full specific dynamic (one module) without requiring the complete model understand (DIETRICH et al., 2019). Table 1 presents a brief description of MAgPIE modules. In the following sections, I describe the main dynamics related to the present research and the appropriate modules that deal with these dynamics.

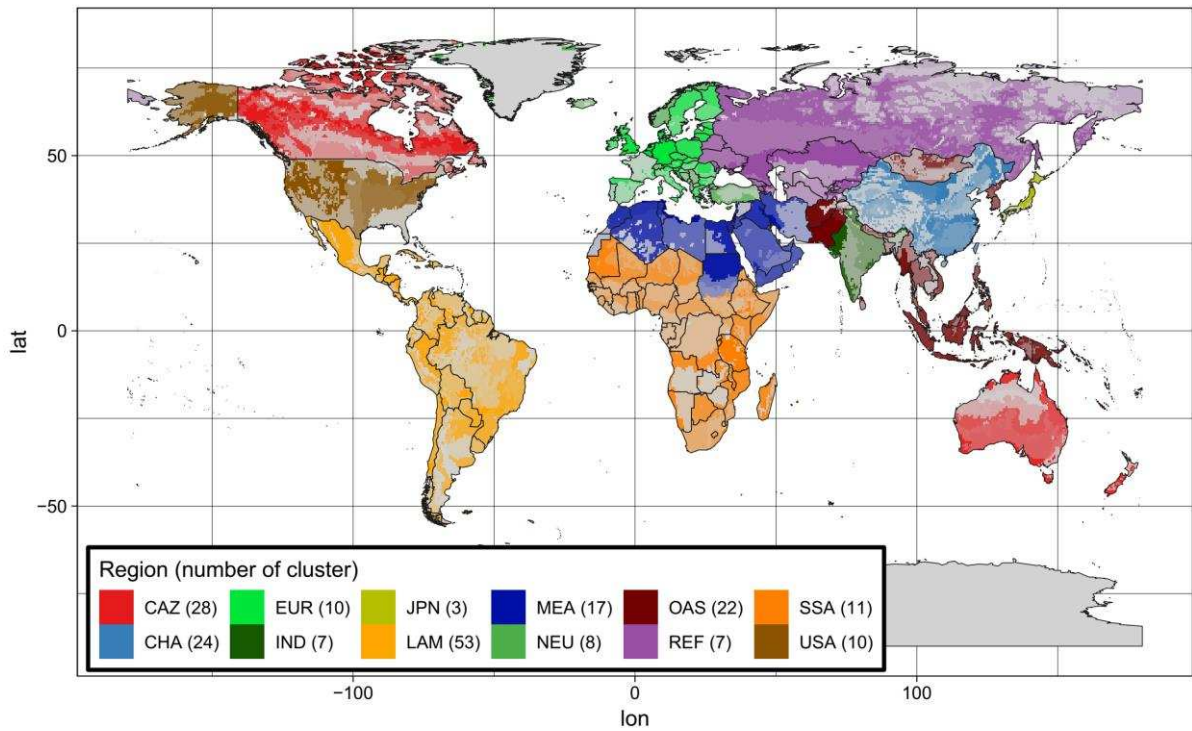


Figure 1. MAGPIE regions and cluster set up: 12 equally treated world regions with 200 clusters in total (DIETRICH et al., 2019).

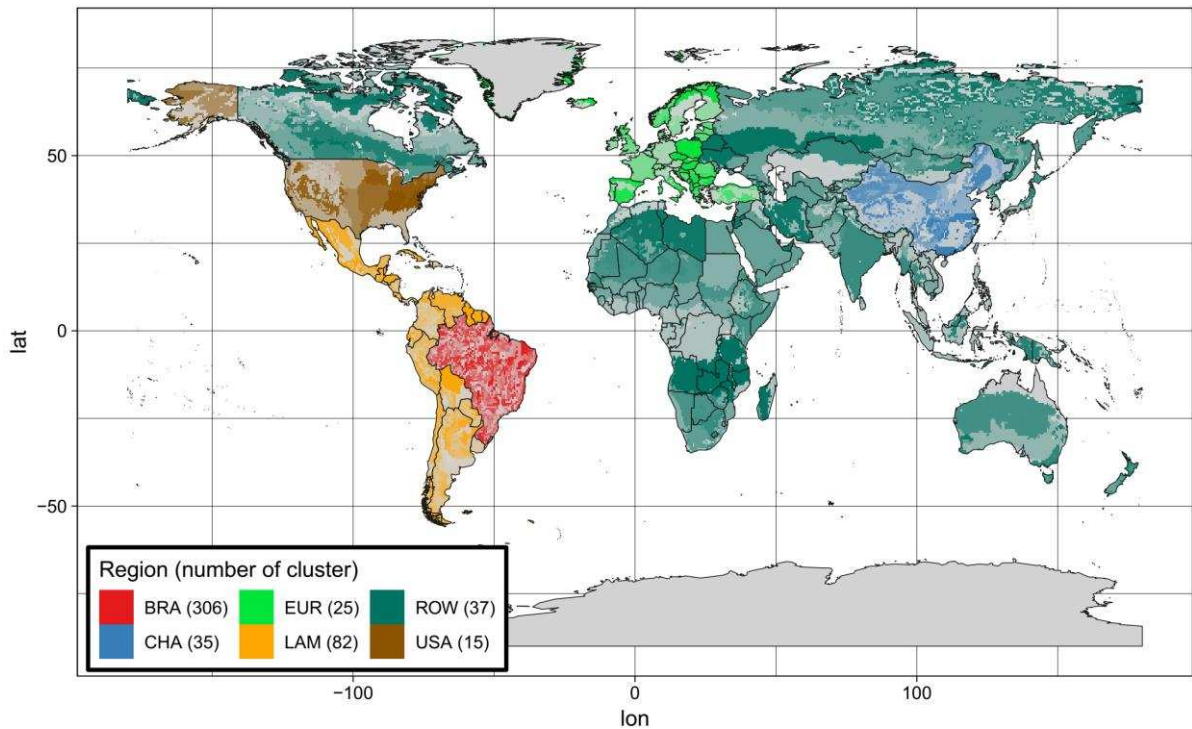


Figure 2. MAGPIE-Brazil regions and cluster setup: 6 regions and 500 clusters in total. Brazil (BRA) and Rest of Latin America (LAM) in increased proportional number of clusters whereas Rest of the World (ROW) in decreased proportional number of clusters (DIETRICH et al., 2019).

Table 1. MAgPIE modules short description

Module name	Short description
drivers	Provides model drivers like population and income that are used by multiple other modules.
land	Simulates spatial competition of different land cover types for physical area.
costs	Calculates total costs by summing up all costs in the model including production costs, investments in R&D or land expansion, tax expenditures, and mitigation costs.
interest rate	Provides interest rates. Accounts for region development level and socioeconomic assumptions.
tc	Links investment into technological change to corresponding yield increases.
yields	Estimates crop and pasture yields based on biophysical yield patterns from LPJmL and endogenous yield-increasing technological change. Biophysical patterns can optionally include climate change impacts.
food	Estimates food demand and dietary composition based on anthropometric food requirements and economic dynamics, accounting for changes in food elasticities due changes in food prices.
demand	Aggregates demand for food, feed, seed, material and bioenergy as well as supply chain losses.
production	Aggregation of agricultural production from cluster to region. Currently, cluster level production is available only for plant commodities, i.e for crops and pastures.
residues	Simulates crop residues, which can be used for feed, recycled to soils and other purposes.
processing	Simulates the mechanical or chemical processing required for primary products to produce secondary products, like from sugar cane to sugar and ethanol.
trade	Simulates trade between world regions based on cost 50 competitiveness and historical trade patterns.
crop	Simulates the dynamics of cropland, crop production and Carbon content in cropland.
past	Simulates the dynamics of pastureland, pasture production and Carbon content in pastureland.
forestry	Describes the constraints for managed forest occurrence and its Carbon content.
urban	Describes urban settlement areas and estimates their corresponding Carbon content.
natveg	Determine availability of primary forest, secondary forest and other natural land for conversion and its Carbon content.
factor costs	Calculates factor costs based on labor, capital, and energy related costs.
landconversion	Calculates the costs for conversion between different land types.
transport	Calculates transport costs of inputs and products between farm and next market-city.
area equipped for irrigation	Constrains irrigated crop production to those areas that are equipped with irrigation infrastructure and simulates the evolution of areas equipped for irrigation.
water demand	Water demand estimation for agriculture, industry, electricity, domestic and ecosystem.
water availability	Water availability based on surface water, groundwater and technical (like desalination).
climate	Provides climatic zones information at cluster level to be used as parameters in other modules.
nr soil budget	Simulates nitrogen flows for crop and pasture soils, demand and costs for inorganic fertilizer.
nitrogen	Estimates nitrogen-related emissions in the forms of N <sub>2</sub> O, NH <sub>3</sub> , nox, NO <sub>3</sub> <sup>-</sup> , and N <sub>2</sub> .
carbon	Estimates terrestrial Carbon stock changes and emissions, aggregating over different land types and accounting for climate change effects.
methane	Estimates Methane emission from enteric fermentation, animal waste management, and rice.
awms	Calculates animal waste management system related to feed, manure, nitrogen and methane.
ghg policy	Connects emissions to costs creating incentives to reduce emissions in case of mitigation policy.
maccs	Marginal abatement cost curves to reduce GHG emissions by undertaking mitigation measures in exchange for additional mitigation costs.
som	Soil organic matter calculates soil organic Carbon loss due to land use activities and nitrogen release due to the soil organic Carbon turnover.
bioenergy	Provides a regional and crop-specific bioenergy demand and its associated production costs.
material	Derives the demand for non-energy material usage like for cosmetics, chemical usage or textiles.
livestock	Estimates the feed demand required to produce livestock products accounting for changing feed mix and feed conversion efficiencies under exogenous increases in livestock productivity.
disagg lvst	Distributes regional livestock production spatially among cells belonging to this region by distributing it close to fodder and pasture production and to urban areas.
optimization	Minimizes total costs of the optimization problem for each time step. Allows for using different optimization strategies to reduce run time.

Source: Adapted from Dietrich et al. (2019) and from Dietrich et al. (2018a).

### 2.3.1. The cost minimization function

MAGPIE minimizes a goal cost function under the constraint of fulfilling an exogenous demand for food and other specific restrictions. For doing so, diverse modules calculate their costs and deliver their calculations to the costs module. The costs module aggregates the global costs of production ( $vm\_cost\_glo$ ), which is the sum of each region's (i) production cost ( $v11\_cost\_reg$ ):

$$vm\_cost\_glo = \sum_i v11\_cost\_reg_{(i)}$$

Region's production cost is represented by the sum of the cost of different production activities. The function is described in the following and its components are described in Table 2 and Table 3:

$$\begin{aligned} v11\_cost\_reg_{(i)} = & \sum_k vm\_cost\_prod_{(i,k)} + \sum_{i,j,land} vm\_cost\_landcon_{(j,land)} + \sum_{i,j,k} vm\_cost\_transp_{(j,k)} \\ & + vm\_tech\_cost_{(i)} + vm\_nr\_inorg\_fert\_costs_{(i)} + vm\_p\_fert\_costs_{(i)} \\ & + vm\_emission\_costs_{(i)} - vm\_reward\_cdr\_aff_{(i)} + vm\_maccs\_costs_{(i)} \\ & + vm\_cost\_AEI_{(i)} + vm\_cost\_trade_{(i)} + vm\_cost\_fore_{(i)} \\ & + vm\_cost\_processing_{(i)} + vm\_costs\_overrate\_cropdiff_{(i)} \end{aligned}$$

After module costs aggregate all production costs, data is delivered to the module optimization in order to achieve the best feasible solution for the cost minimization problem for each time step (t). The cost minimization occurs under diverse constraints that can be placed at any geographical level and time step, according to the representation of a real-world dynamic. In the following sections, I briefly describe the two main dynamics for the purposes of the present research. Firstly, the LUC dynamics, including agricultural land and deforestation and the decisions related to land expansion and land intensification. Secondly, the implementation of the deforestation mitigation targets for Legal Amazon and Cerrado as constraints to the model.

Table 2. Cost of different product activities

Cost	Description
vm_cost_AEI (i)	Irrigation expansion costs
vm_cost_fore (i)	Afforestation costs
vm_cost_landcon (j, land)	Land conversion costs
vm_cost_processing (i)	Processing costs
vm_cost_prod (i, k)	Factor costs
vm_costs_overrate_croplanddiff (i)	Punishment costs for overrated cropland difference
vm_cost_trade (i)	Regional trade costs
vm_cost_transp (j, k)	Transportation costs
vm_emission_costs (i)	Costs for emission rights for pollutants and GHGs
vm_maccs_costs (i)	Costs of technical mitigation of GHG emissions
vm_nr_inorg_fert_costs (i)	Costs of inorganic fertilizers
vm_p_fert_costs (i)	Costs for mineral fertilizers
vm_reward_cdr_aff (i)	Revenues for Carbon captured by afforestation
vm_tech_cost (i)	Costs of technological change

Source: Adapted from Dietrich et al. (2018a).

Table 3. Sets description

Set	Description
i	Region
j	Cluster
k	Product
land	Land type

Source: Adapted from Dietrich et al. (2018a).

### 2.3.2. Land-use change and deforestation

MAGPIE has seven diverse land types: urban, cropland, pastureland, forestry, primary forest, secondary forest, and other land. Urban is the only static land type with the spatial distribution of 1995 and the others are dynamic over time. Cropland is the area for cultivating the 19 different crops, including crops for food, for feed and bioenergy crops. Pastureland is the area for pasture, which is one of the inputs for livestock products. Agricultural land accounts for pastureland plus cropland. Forestry is defined as areas of afforestation and reforestation due to afforestation and based on FAO Forest Resources Assessments (2019) and is also referred as managed forest. Primary forest is untouched forest and secondary forest has been modified by human activities somehow. Full-grown primary forest and full-grown secondary forest have the same carbon content, but secondary forest has lower carbon density on its age-classes. Data on primary and secondary forests are based on Land-Use Harmonization 2 (LUH2) (2019) and internally calibrated to match FAO Forest dataset. Forestland accounts for the sum of forestry, primary forest, and secondary forest. Other land is all natural land that is not

forestland neither agricultural land neither urban. It includes deserts, mountains, and savannahs, and abandoned agricultural land. Natural land accounts for the sum of forestland and other land.

Land-use change across land types occurs when the share of the diverse land types change over time in a specific area (cluster, region, or any area defined). Deforestation is a specific kind of land-use change that occurs when the share of forestry, primary forest or secondary forest decrease over time in a specific area. There are diverse drivers determining land-use change like food and feed demand, yields, land conversion costs, technological change costs, water availability, interest rate, and trade. In addition, there are diverse inputs, assumptions, parameters and other settings defining these drivers.

Taking land-use dynamics from the perspective of the products  $k$ , it starts by the adoption of yields calculated by LPJmL, which defines it at the cluster level  $j$ , for all the time steps  $t$ , for each product  $k$ , for each RCP. Before the optimization, MAgPIE calibrates the yields from LPJmL in order to make cropland and pastureland, in each region, to meet the historical area from FAO for the year 1995. This procedure assures that MAgPIE area estimates are as close as possible to the values reported by FAO to 1995.

The model endogenously decides for the agricultural land to reduce, expand, intensify or maintain it as it is, at each cluster, for each product, at each time step, according to the demand for food, feed, bioenergy, and materials. Therefore, the diverse demand types are the initial drivers of land-use change. Higher global demand would promote agricultural land expansion or intensification. Lower global demand would lead to an agricultural land reduction. Moreover, there are cases in which, even with constant demand, the model may change its current land-use set up, relocating production and, or, invest in technological change (intensification). When moving from one time step to the next, the model starts the optimization to minimize the cost function taking into account the optimal solution from the previous time step.

Agricultural land expansion occurs when the share of pastureland or cropland increases over time in a specific area (cluster, region, or any area defined) and if it decreases there is an agricultural land reduction. Production of products  $k$  drives agricultural land dynamics. The production of one specific product may increase in one region and production of another product decrease in the same region, counterbalancing the cropland dynamic. The production of a product  $k$  may be shifted to another cluster inside the same region if there are more attractive biophysical conditions, without changing regional cropland area, but changing the cropland geographical location.

Moreover, if one cluster were biophysically more attractive, region total cropland would also shrink as more attractive conditions mean higher yields. The land-use dynamics inside a region may not affect its total agricultural area, but changing the location where a product is produced may present cluster level implications to the model in the optimization process.

If agricultural land reduces, the abandoned land becomes other land. If other land remains untouched over time, the model assumes natural succession (e.g. regrowth of vegetation) along specific Carbon content pathway. If the vegetation carbon density passes a threshold of 20 ton Carbon/ha the respective area is moved from other land to secondary forest. As this is a natural regrowth, this is not accounted as forestry. In addition, as each land type in each cluster has a specific Carbon content pathway, the low Carbon content of desert areas ensure that those areas will never become secondary forests. Change of Carbon stocks is calculated as a difference between the current and the previous time step, for each land type, at each cluster, and determine LUC CO<sub>2</sub> emissions. Therefore, there can be CO<sub>2</sub> emissions for any kind of land-use change, not just for deforestation. Methane emissions are calculated from enteric fermentation, which depends on the feed quality and the purpose of livestock farming, animal waste management, and rice production. Nitrogenous emissions include N<sub>2</sub>O, NO<sub>x</sub>, NH<sub>3</sub>, NO<sub>3</sub>- and N<sub>2</sub> and its sources are manure applied to cropland, inorganic fertilizers, and animal waste management, among others.

Technological change for crops usually represents a high initial investment that pays off in the long term by increasing the yields. The decision for investing in it considers interest rates, investment horizon, current yields, and technological change costs. The higher the current crop yields are, the more expensive it is to increase crop yields even more. Technological change in MAgPIE do not differentiate between crops, i.e. investments made for the crop will increase the productivity of all crops in the region. Investments in technological change to increase crop yields occur as a response to increasing demand and increasing land competition. Investments in technological change to increase pasture yields, however, only occur as a response from demand dynamics. It relates to an exogenous pasture management factor based on a demand-side proxy for a growth rate of cattle stocks. For example, if the growth of Brazilian cattle stock increases due to livestock relocation from other countries, then the pasture yield increase as well. One limitation of this approach is that the exogenous implementation cannot capture feedbacks between land scarcity and efforts to improve pasture management. MAgPIE is

only able to intensify pasture production due to increased pasture demand, but not due to increased land competition.

Changes in global food and feed demand are composed by changes in regional demand. Changing regional demand would lead, besides expansion and intensification, to changes in the trade patterns. If one region has a higher demand for a product, another region can produce the product and trade it with the demanding region. By this way, the interconnected global markets can displace agricultural production, as well as deforestation, among diverse regions. International transactions imply costs while there is no representation for transactions costs inside the same MAgPIE region.

### **2.3.3. National Policies Implemented (NPIs)**

The National Policies Implemented (NPIs) are the policies to avoid deforestation and, or, to promote afforestation that are documented as ongoing policies in each country's NDC. NDCs also state future commitments, measures and targets, however, in the present research, only ongoing policies (NPIs) are set in the model. NPIs implementation from the NDC documents enables representation of national policies in a globally consistent way. For some countries, further investigation for better NPI implementation was required. Specifically for Brazil, the PPCDAm (BRASIL, 2018a) and PPCerrado (BRASIL, 2016) deforestation mitigation targets were implemented as NPIs besides other mitigation measures stated by Brazilian NDC. In the case of avoiding deforestation, its implementation is by protecting forestland (forestry, primary forest, and secondary forest) in the policy area, which represents the achievement of the countries' mitigation of deforestation targets. Forestland protection is a constraint to the model implemented at the grid level and aggregated to the cluster level through Clusterization (section 2.2.2). FAOSTAT (2016) is the basis for calculating deforestation reduction target in the cases that changes in forestland stock over time is part of the calculations to define the target mitigation.

Brazilian NPIs for Legal Amazon and Cerrado are described in the following<sup>13</sup> and Figure 3 depicts the policy area and Brazilian regions and biomes:

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<sup>13</sup> There are other NPIs for Brazil in the model that are not a focus of the present research. Relating to deforestation, NPI for Atlantic Forest fully protects its forestland since 1995. Relating to afforestation, NPI states 3 million ha afforestation in the country between 2010 and 2020. In the present research, MAgPIE-Brazil have these two NPIs always set on.

- NPI for Legal Amazon: Deforestation in Legal Amazon in 2020 must be 80% below deforestation in 2005. Policy starts in 2005.
- NPI for Cerrado: Deforestation in Cerrado in 2020 must be 40% below deforestation in 2010. Policy starts in 2010.

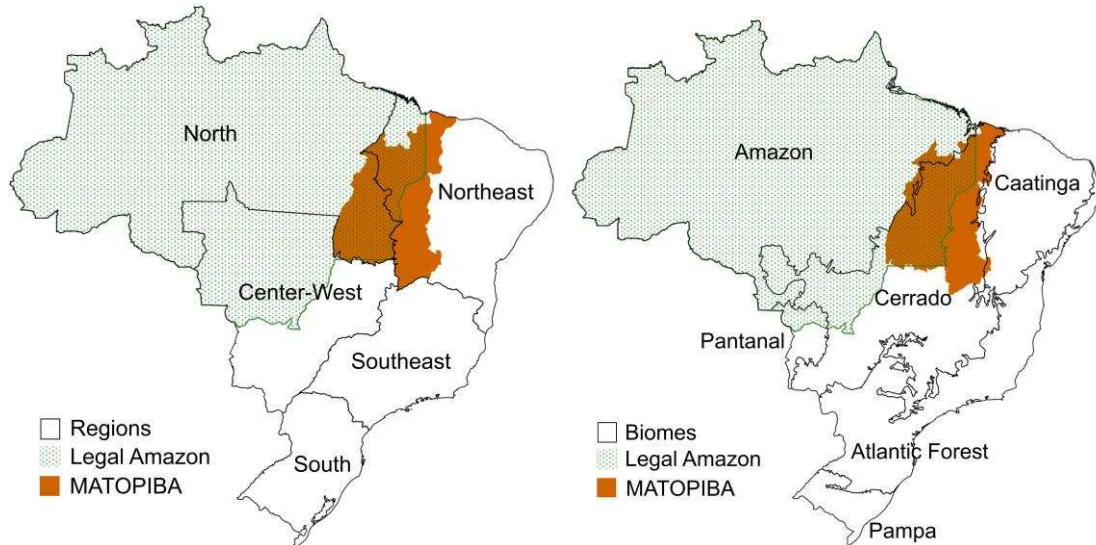


Figure 3. Brazilian regions (left), biomes (right), Legal Amazon and MATOPIBA.

In the area where Legal Amazon overlaps Cerrado, I assumed the deforestation target used for Legal Amazon as the constraint to the model because it is more ambitious. The constraints follow a linear pathway from the initial to the final year of the policy. For example, for Cerrado the required reduction of deforestation in 2010 is 0%, in 2015 is 20% and in 2020 is 40% (the target year with the full target reduction deforestation). This leads the model to increasingly reduce deforestation instead of keeping deforesting during the course of the policy and only reduce deforestation in the target year. In addition, I assume that deforestation will remain below the target after the target year, keeping the target value as a constraint to the model in the following time steps. The Brazilian NPIs for deforestation are determinant to answer the second research question, as the comparison of scenarios with NPIs on and off defines the impacts of the deforestation policies.

#### 2.4. Biophysical and Socioeconomic scenario-based analysis

The RCPs and SSPs were developed in order to cover a broader range of plausible biophysical and socioeconomic pathways, independently one from the other. The main objective of the RCP development was to provide information on conceivable development paths for the main forcing agents of climate change (MOSS et al., 2010)

measured in Watts per square meter ( $W/m^2$ ) in which the value in the year 2100 names the pathway (Table 4). The RCPs do not intend to describe the drivers that lead to the forcing values, however the four RCPs were designed to be representative of the total plausible scenarios in terms of emissions and concentrations available by 2100 (VAN VUUREN et al., 2011). On the socioeconomic side, the SSPs were developed taking challenges for mitigation and adaptation into account to represent plausible future scenarios (Table 5) based on six broad groups of features (O'NEILL et al., 2017): demographics, human development, economy and lifestyle, policies and institutions (excluding climate policies), technology, and environment and natural resources. Although they depict broadly diverse futures, there is no likelihood attached to any of them and they are all possible pathways (VAN VUUREN et al., 2011). Table 4 and Table 5 shortly describe the RCPs and SSPs, respectively

Although the design of RCPs and SSPs was orthogonal, they present some internal consistency. By modeling SSPs assumptions into IAMs, it is possible to derive a radiative forcing correlated the SSPs. Riahi et al. (2017) demonstrated that SSP1 assumptions would lead to RCP6.0 in 2100 if no mitigation efforts were taken and that SSP5 would lead to RCP8.5. The authors argued that SSP1 is a baseline for RCP6.0 and SSP5 is a baseline for RCP8.5. Similarly, in MAgPIE, for a given SSP to reach a lower radiative forcing in 2100 additional global mitigation measures should be applied to the model. The approach for such mitigation is a global Carbon emission price, which incentivizes Carbon sequestration (afforestation) and emission reductions (prevent deforestation and enhances the use of bioenergy instead of fossil fuel). MAgPIE uses specific RCPs-SSPs Carbon emission prices for each feasible RCP-SSP association. As a rule, RCP2.6 requires higher Carbon emission prices than RCP8.5, which actually do not require it. SSP5 (energy based development), by its turn, requires higher Carbon emission prices than SSP1 (sustainable development). Due to the high socioeconomic demands in SSP3, it is infeasible to for this SSP to achieve RCP2.6, therefore RCP2.6-SSP3 scenario is excluded from the present research.

Table 4. Short description of RCPs.

RCP	Short description
RCP2.6	Radiative forcing peaks at $\sim 3$ W/m <sup>2</sup> ( $\sim 490$ ppm CO <sub>2</sub> eq) before 2100 and then declines to 2.6 W/m <sup>2</sup> by 2100. This pathway is consistent with achieving the 2°C warming target.
RCP4.5	Emissions stabilization without overshoot pathway to 4.5 W/m <sup>2</sup> ( $\sim 650$ ppm CO <sub>2</sub> eq) at stabilization after 2100.
RCP6.0	Emissions stabilization without overshoot pathway to 6.0 W/m <sup>2</sup> ( $\sim 850$ ppm CO <sub>2</sub> eq) at stabilization after 2100.
RCP8.5	Continuous rising of radiative forcing that leads to 8.5 W/m <sup>2</sup> ( $\sim 1370$ ppm CO <sub>2</sub> eq) by 2100.

Source: develop by the author based on Van Vuuren et al. (2011).

Table 5. Socioeconomic challenges and short description of SSPs

SSP	Socioeconomic challenges for		Short description
	mitigation	adaptation	
SSP1	low	low	Depicts a sustainable development world and a break with recent history.
SSP2	medium	medium	Business as usual scenario; it represents a continuation of the trends observed in the last century.
SSP3	high	high	Reflects international fragmentation and a world characterized by regional rivalry.
SSP4	low	high	It is characterized by inequality, in which developing countries are still pursuing development.
SSP5	high	low	Represents accelerated globalization and rapid development of developing countries and high dependency on energy (which can come from fossil fuels or from bioenergy, depending on the RCPs assumptions).

Source: develop by the author based on O'Neill et al. (2017).

The Carbon prices required to achieve RCP6.0, for all SSPs, are relatively low. Therefore, I used RCP6.0 with no Carbon emission prices and named it no-mitigation scenario. In this scenario, the climate change effects associated with RCP6.0 are considered but there is no global incentive to mitigate emissions. On the opposite, RCP4.5 requires high Carbon emission prices in order to mitigate emissions to achieve their radiative forcing levels and RCP2.6 requires even higher Carbon emission prices. Therefore, I use global Carbon emission prices as the tool to mitigate emissions in RCP4.5 and RCP2.6 and name them mitigation scenarios. This is the usual approach to force

IAMs to meet a certain RCP, as presented by POPP et al. (2017), and is also used for global land-use models in the same perspective, as for MAgPIE (DIETRICH et al., 2019). MAgPIE uses Carbon prices previously calculated by IAMs consistent with each RCP-SSP scenario. The Carbon prices for RCP4.5-SSP4 and RCP2.6-SSP4 come from GCAM4, prices for RCP4.5-SSP3 come from AIM-CGE and prices for all other SSPs-RCPs come from REMIND-MAgPIE.

The RCPs and SSPs also play another role in MAgPIE in order to reflect the assumptions they are related to. The RCPs directly affect the Carbon content in the vegetation and soil, yields, water availability, and water demand. LPJmL process all these data and deliver it as inputs to MAgPIE, at the grid level (which is upscaled to cluster level through clusterization), according to each RCP. LPJmL's inputs directly affect the following modules in MAgPIE: yields, carbon, water demand, water availability, som, and ghg policy. The SSPs, by its turn, include specific population and income pathway and specific storylines regarding other socioeconomic features. Besides using population and income to calculate the demand, MAgPIE also translates the SSP's storylines as specific settings in the following modules, at the regional level: drivers, food, ghg policy, bioenergy, material, livestock. Therefore, each RCP-SSP scenario is one specific representation of socioeconomic and biophysical assumptions, including specific inputs and settings.

### 3. RESULTS AND DISCUSSION

#### 3.1. Brazilian future land-use dynamics

In this subsection, I present and discuss the dynamics of 14 RCP-SSP scenarios: RCP6.0 (no-mitigation) in SSP1, SSP2, SSP3, SSP4, SSP5; RCP4.5 (mitigation) in SSP1, SSP2, SSP3, SSP4, SSP5; and RCP2.6 (mitigation) in SSP1, SSP2, SSP4, SSP5. I present graphs for all RCP-SSP scenarios and figures presenting changes in shares of specific variables for all RCPs in the SSP2. I assess the following outputs for Brazil: food and feed demand, natural land, CO<sub>2</sub> emissions from LUC, agricultural land, production, yields, net-trade, and food price index. MAgPIE-Brazil runs from 1995 to 2060 in a 5-year time step and from 2060 to 2100 in a 10-year time step. The year 1995 is the starting year for analyzing the graph outputs, except for the food price index, which the base year is 2010. Model validation is ensured by i) historical data in the graphs from FAOSTAT (2016), MapBiomass (2019)<sup>14</sup> and LUH2v2 (2018), ii) comparisons of model outputs to observed data and to other researches; iii) the evaluation documents with all model outputs and validation data available online (AMBRÓSIO, 2019b).

##### 3.1.1. Food and feed demand

The main drivers of demand are population and income, which are defined by the SSPs, therefore, there are important differences in demand regarding the diverse SSPs (Figure 4). Brazilian population in SSP2 increases from 213.1 million people in 2020 to 231.9 in 2045 and then decreases. Projection in SSP3 is higher than in SSP2 and

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<sup>14</sup> Validation data from MapBiomass (2019) required methodological assumptions to associate original data to MAgPIE variables. The most important assumption regards the variable “Mosaico de Agricultura ou Pastagem” (Mosaic of Agriculture or Pasture) from MapBiomass, which aggregates unidentified data of pasture or cropland. The variable was distributed for MAgPIE validation as cropland and pastureland according to the share cropland/pastureland in order to prevent underestimation of pastureland and cropland validation data. This procedure and the methodological approach from using MapBiomass data as validation in MAgPIE are detailed in Appendix 1 and Figure A1.

projections in all other SSPs are roughly similar and lower than in SSP2. Projection in SSP2 is the closest to the Brazilian official projection, which increases from 211.7 million people in 2020 to 233.2 in 2047 (INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA (IBGE), 2019). Brazilian income in SSP2 increases by 31% from 2015 to 2025, 105% from 2015 to 2050 and 363% from 2015 to 2100. Projections in SSP2 are somehow close to projections from other institutes, as an increase of 25% from 2015 to 2023 (WORLD ECONOMIC OUTLOOK, 2018) and an increase of 110% from 2016 to 2050 (PRICEWATERHOUSECOOPERS, 2017). Projection in SSP5 is the highest, followed by SSP1 and SSP4, all of them are higher than in SSP2. Income projection in SSP3 is the lowest.

As a rule, SSP3 and SSP2 present the higher food and feed demand for Brazil and globally (Figure A2 and Figure A3, Appendix 2). SSP1 has the lower food and feed demand. On the other side, Figure 4 presents a similar picture for Brazilian food and feed demand when analyzing one specific SSP among the diverse RCPs. The main drivers of demand are defined by the SSPs, but the RCPs can also affect it by yields and price. For example, climate change (RCPs) affects pasture yields, which changes the relative prices from pasture related products to other food goods and the changes in relative price affect the demand. Moreover, a positive trend in temperature in Brazil from 1980 to 2008 is associated with lower maize and soybean yields (LOBELL; SCHLENKER; COSTA-ROBERTS, 2011), which are some of the main components of feed demand.

The bioenergy demand, by its side, represents a structural change over fossil fuels that is required to achieve RCP4.5 and RCP2.6. A greater substitution from fossil fuel to bioenergy is required in the lower RCPs. SSP5 depicts high energy demanding scenarios. If it is associated with RCP6.0, its energy may come from fossil fuels, but if it is associated to RCP2.6, its energy mainly comes from bioenergy. Therefore, bioenergy demand is higher in RCP2.6-SSP5.

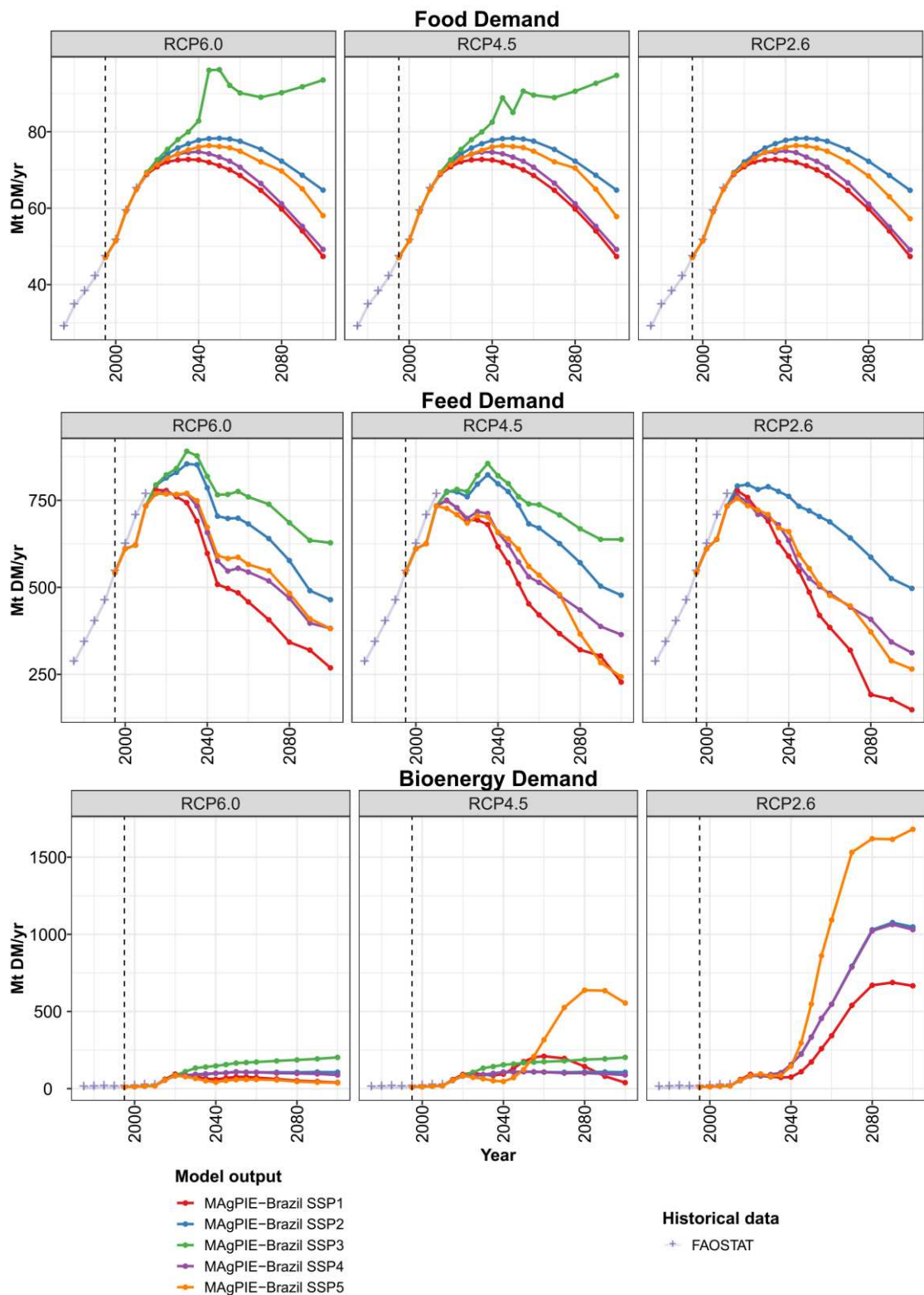


Figure 4. Brazilian food, feed and bioenergy demand.

### 3.1.2. Natural Land

Forestland projections move away from FAOSTAT data since the initial periods, which is a recurrent issue in MAgPIE and MAgPIE-Brazil. In the case of Brazilian projections, low yield pastures in northern South region are abandoned from

2000 to 2005, which lower deforestation rate and distance forest stock projections from observed forest stock. FAOSTAT states 5.6% deforestation from 2000 to 2015 while MAgPIE-Brazil projects 3.3% deforestation in the same period. On one side, this delay on the projected dynamics compromises total values comparisons. On the other, projected and observed data follow a similar pathway from 2005 to 2015, which enhances its reliability regarding the trajectory of the pathway. LUH2v2 dataset, by its turn, presents much lower forestland than MAgPIE-Brazil projections because MAgPIE is calibrated to match FAO data instead. Therefore, comparisons with LUHv2v dataset is more relevant for the trajectory than for the absolute values.

For all RCP-SSP scenarios, except RCP6.0-SSP3, forestland decreases up to 2030 and then it remains constant or increases (Figure 5). In RCP2.6, afforestation (forestry) also plays an important role. There is a regular increase in forestland that reaches 2100 up to 130 million ha higher than in 2030. The increase in forestland is due to an increase in managed forest (forestry) (Figure A4, Appendix 2), which became economically feasible because of the Carbon emission prices rewarding Carbon sequestration.

Bottom figures in Figure 5 present the location of changes in forestland share. With Brazilian NPIs on, Legal Amazon and Cerrado present only minor decreases in forestland share. In RCP6.0-SSP2, there are small decreases in forestland share in Northeast, South, and Center-West. In RCP4.5-SSP2, there are practically no changes in forestland share. In RCP2.6-SSP2, the increase in forestry (Figure A4, Appendix 2) drives up forestland share in northern of the South, Southeast and in the coastal areas of North and of Northeast. The increased forestland in northern of the South region occur in an area of low pasture yield (see Figure A5 in Appendix 2 for potential yields from LPJmL used as input for MAgPIE in 1995), indicating the model's option to afforest where land has low agricultural potential.

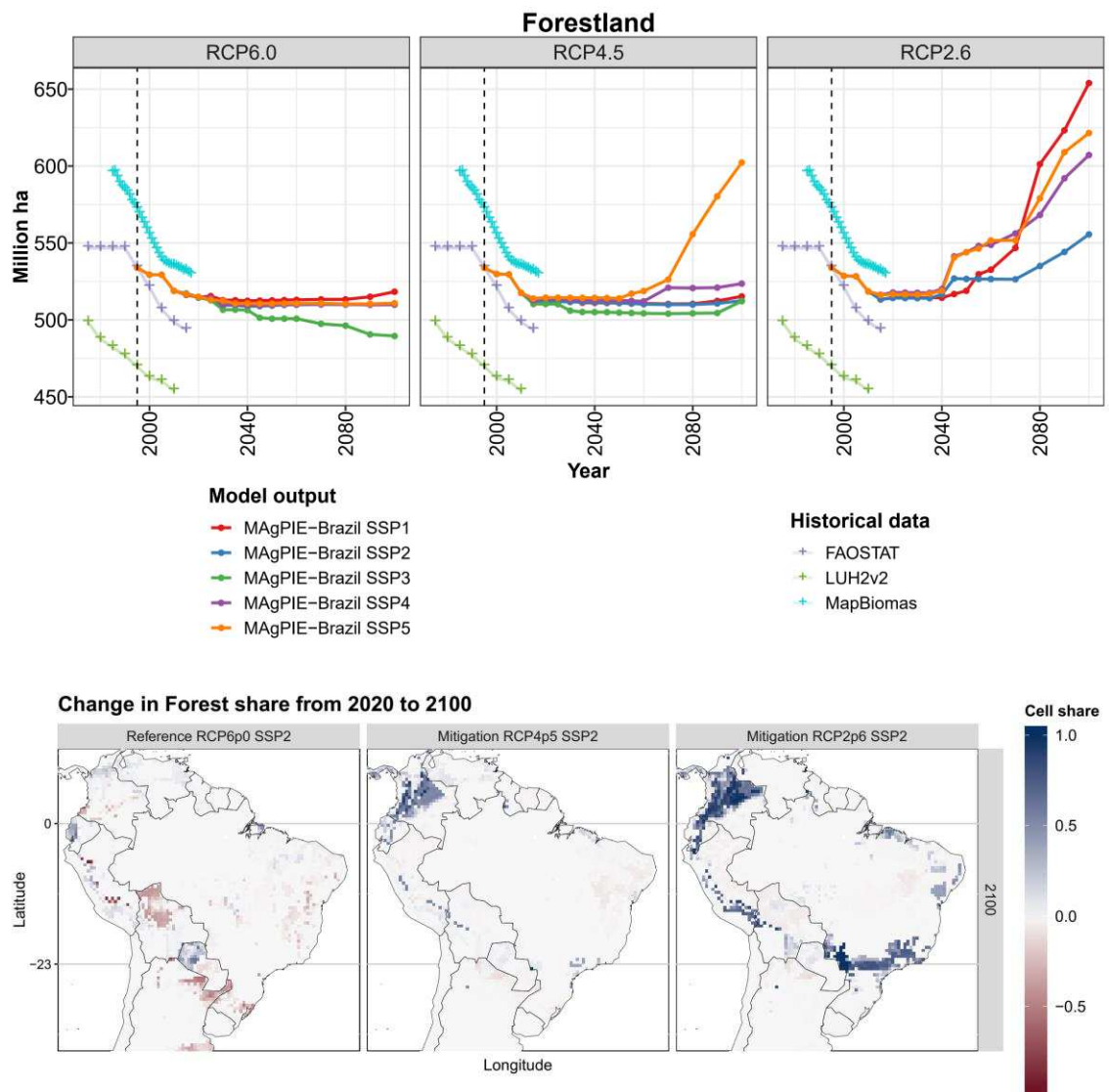


Figure 5. Brazilian forestland and change in forest share from 2020 to 2100.

Other land validation data from FAOSTAT is not available in MAgPIE's validation datasets. The historical dataset for this land type is LUHv2v, whose value is much higher than MAgPIE's projections (Figure 6). Even though there is a mismatch, both of them decreased at a similar path from 1995 to 2010: 7.5 million ha in MAgPIE and 7.1 million ha in LUHv2v. For most of the RCP-SSP scenarios, other land remains constant from 2015 onwards and only present some increase in SSP1 and some decrease in SSP3. Bottom figures in Figure 6 show that other land share decreases in parts of Southeast and Northeast and this effect is higher in RCP6.0-SSP2.

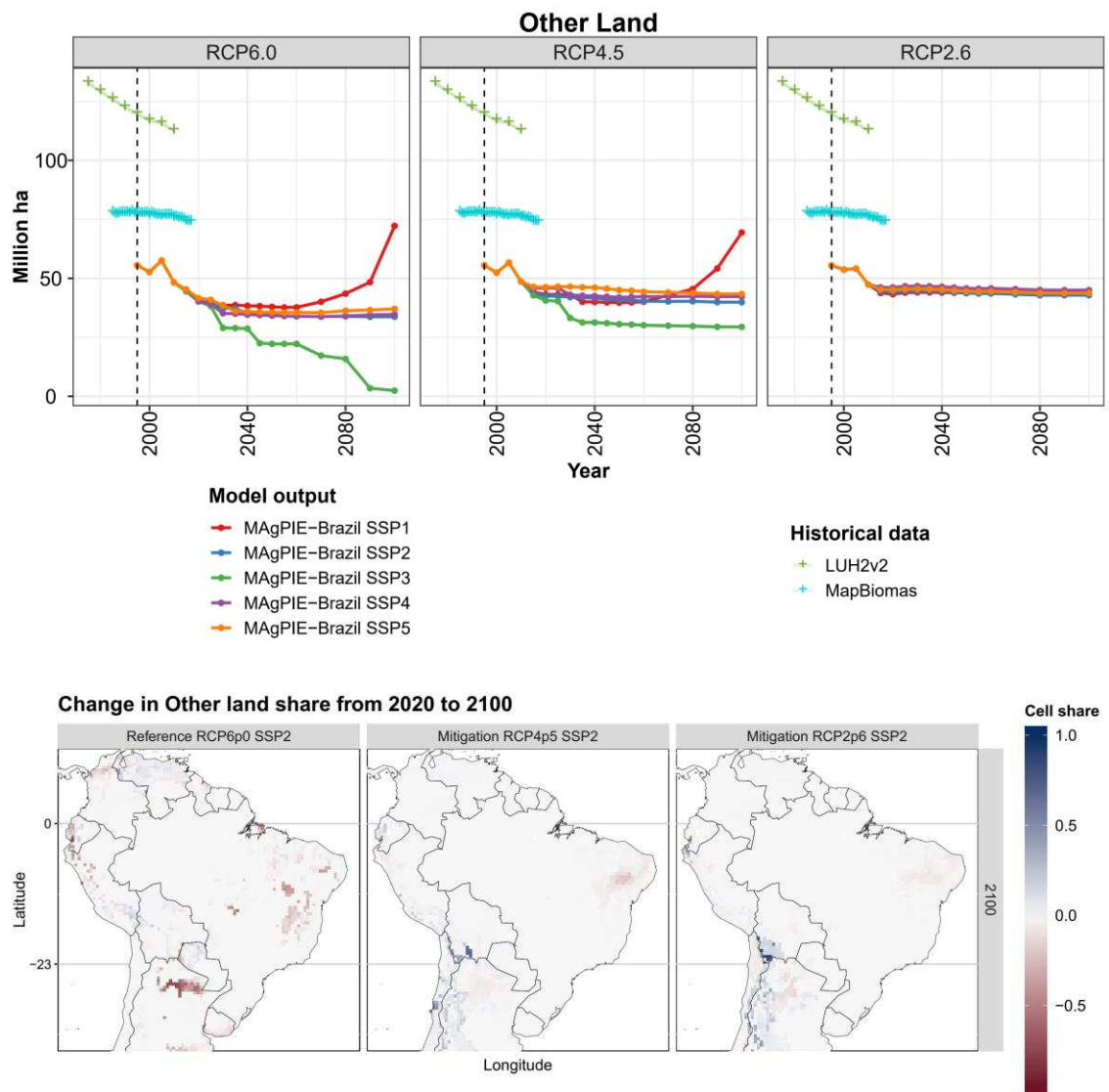


Figure 6. Brazilian other land and change in other land share from 2020 to 2100.

### 3.1.3. LUC CO<sub>2</sub> Emissions

Figure 7 shows cumulative emissions from 1995 to 2100. Although deforestation stops around 2030 in most of scenarios, LUC CO<sub>2</sub> emission remains positive up to 2050, which reflects as increasing cumulative emission in Figure 7. From 2050 onward, LUC emissions stabilize or become negative in most of the scenarios, reflecting as stable or decreasing cumulative CO<sub>2</sub> emissions in Figure 7. From 1995 to 2100, Brazil is projected to accumulate between 9 to 22 Gt CO<sub>2</sub> from LUC in the atmosphere in the RCP6.0 and to sink between 2 to 14 Gt CO<sub>2</sub> from LUC in RCP2.6 (as a consequence of the increase in forestland, see Figure 5). An interesting dynamic occurs in RCP4.5 and RCP2.6. In these RCPs, the SSP1 pathways remain above the SSP2 pathways for most of the period. It indicates that the optimal trajectory in the less

demanding socioeconomic assumptions (SSP1) allows keeping higher emissions to achieve the RCP than in SSP2 (which is more socioeconomic demanding than SSP1).

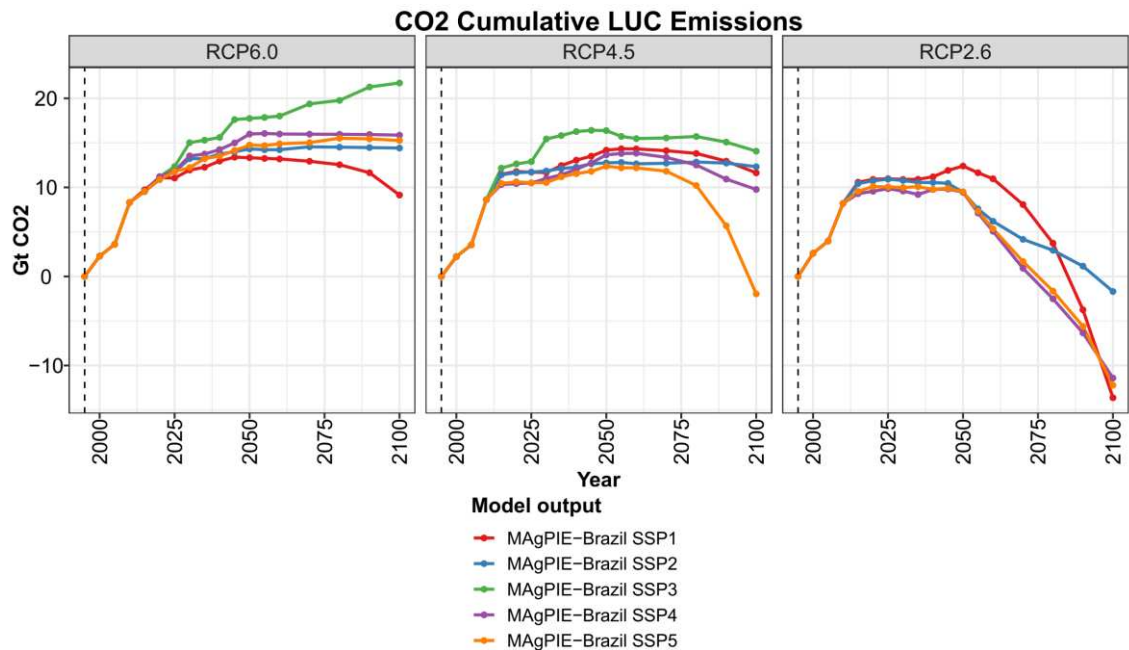


Figure 7. Brazilian CO2 cumulative LUC emissions.

### 3.1.4. Agricultural Land

Brazilian agricultural land (cropland plus pastureland) increases 9% in MAgPIE from 1995 to 2010 and 6.6% in FAOSTAT and 21% in MapBiomass (MAPBIOMASS, 2019) in the same period. The initial agricultural area in 1995 is lower in MapBiomass (198 million ha) than in FAOSTAT and MAgPIE (258 million ha). MAgPIE's projections are designed to match as closely as possible to FAOSTAT data in 1995 in order to assure a global land-use data set, which leads to mismatching MapBiomass observed data.

Figure 8 presents cropland for food, feed and bioenergy crops. Cropland projections follow a similar path in the initial years compared to FAOSTAT and LUH2v2. In RCP4.5 and RCP2.6, the pathways remain roughly similar among the diverse SSPs after the initial years, and in RCP6.0, the pathways are wider. For RCP4.5, the projections are more concise among diverse SSPs, ranging from 100 to 130 million ha and, for RCP2.6, from 60 to 70 million ha. For RCP6.0, cropland range from 85 to 160 million ha in 2100. The higher increase in RCP6.0-SSP3, which has also higher food and feed demand. On the other side, cropland decreases in RCP6.0-SSP1 from 2060 onwards and the abandoned cropland becomes other land. As an overall outcome, the variability of SSPs is narrow in the mitigation scenarios.

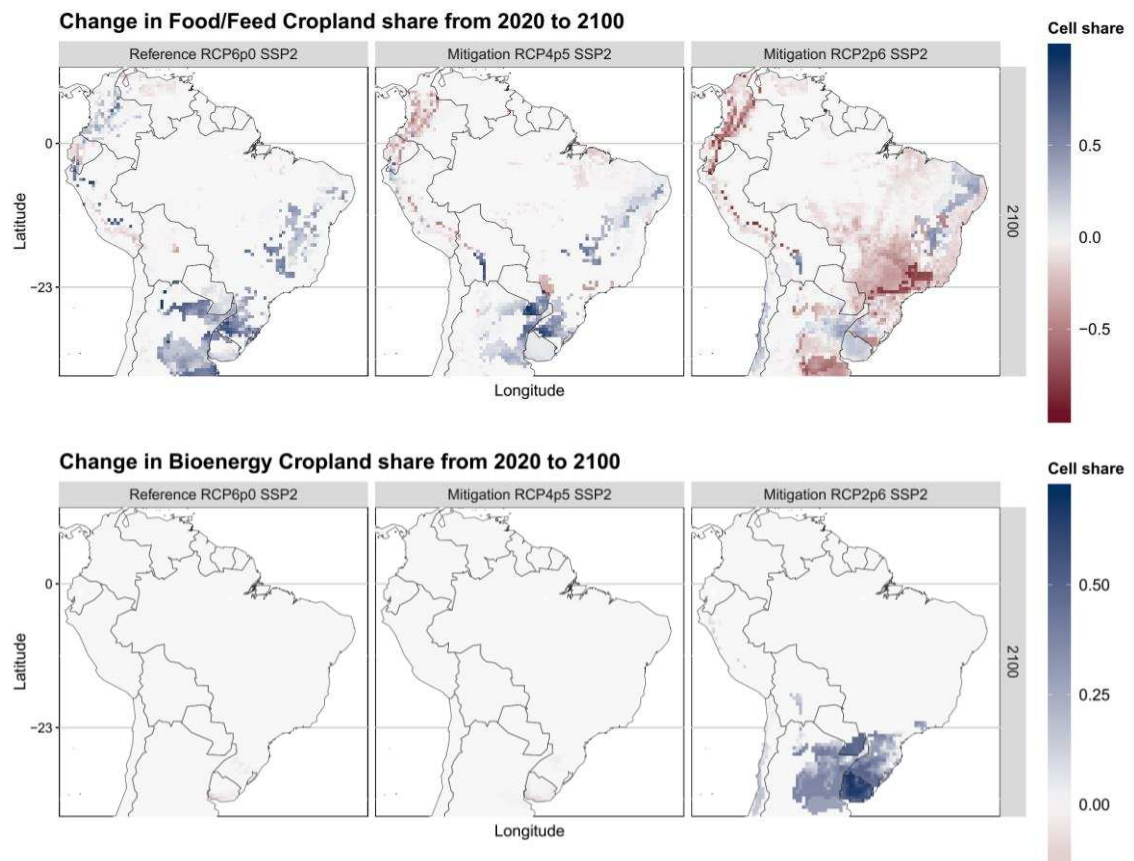
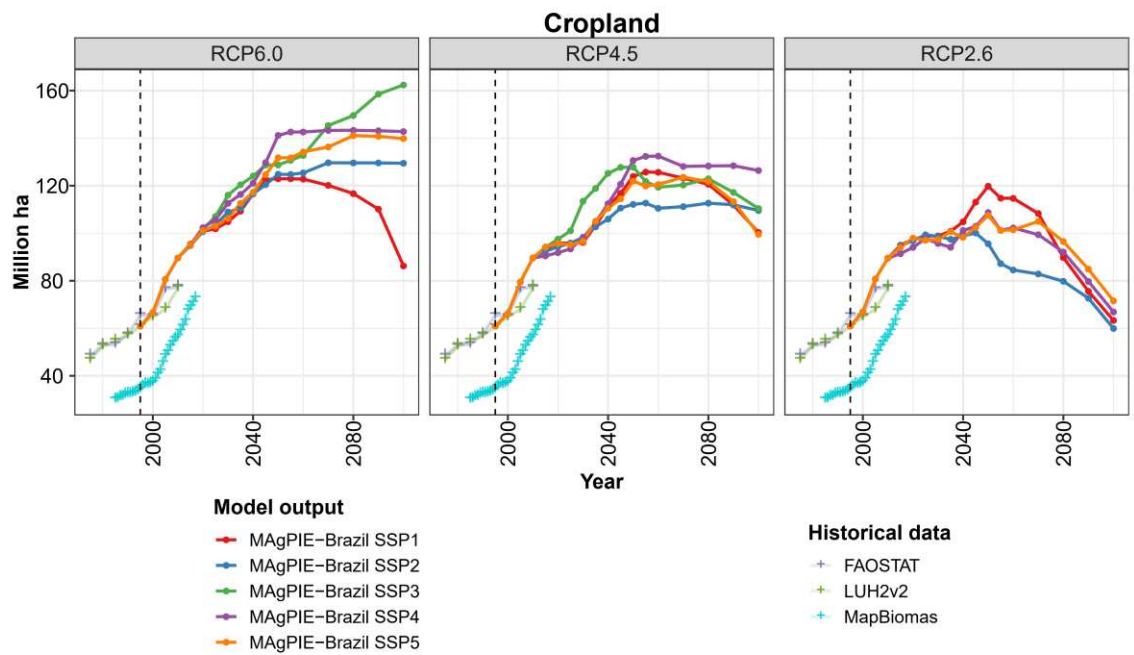


Figure 8. Brazilian cropland, change in food/feed and bioenergy share from 2020 to 2100.

Bottom figures in Figure 8 show that the food/feed cropland share increases in the South, Southeast and Northeast (especially in Caatinga biome) in RCP6.0-SSP2 and RCP4.5-SSP2. On the other side, in RCP2.6-SSP2, cropland share decreases in most

of the country, but still increases in the Caatinga region. The Northeast region has lower yields than other regions (see Figure A5 in Appendix 2 for the case of pasture potential yields from LPJmL used as input for MAgPIE in 1995) and a considerable part of cropland expansion observed in Figure 8 is only achievable due to irrigation. In all RCPs, cropland expands over the same area in which Figure 5 and Figure 6 present forestland and other land decreases, indicating deforestation and depletion of natural land. Bioenergy cropland share increases in South in RCP2.6-SSP2 but its changes in RCP6.0 and RCP4.5 are almost negligible. Most of cropland share decrease in RCP2.6-SSP2 is due to pastureland expansion (presented in Figure 9).

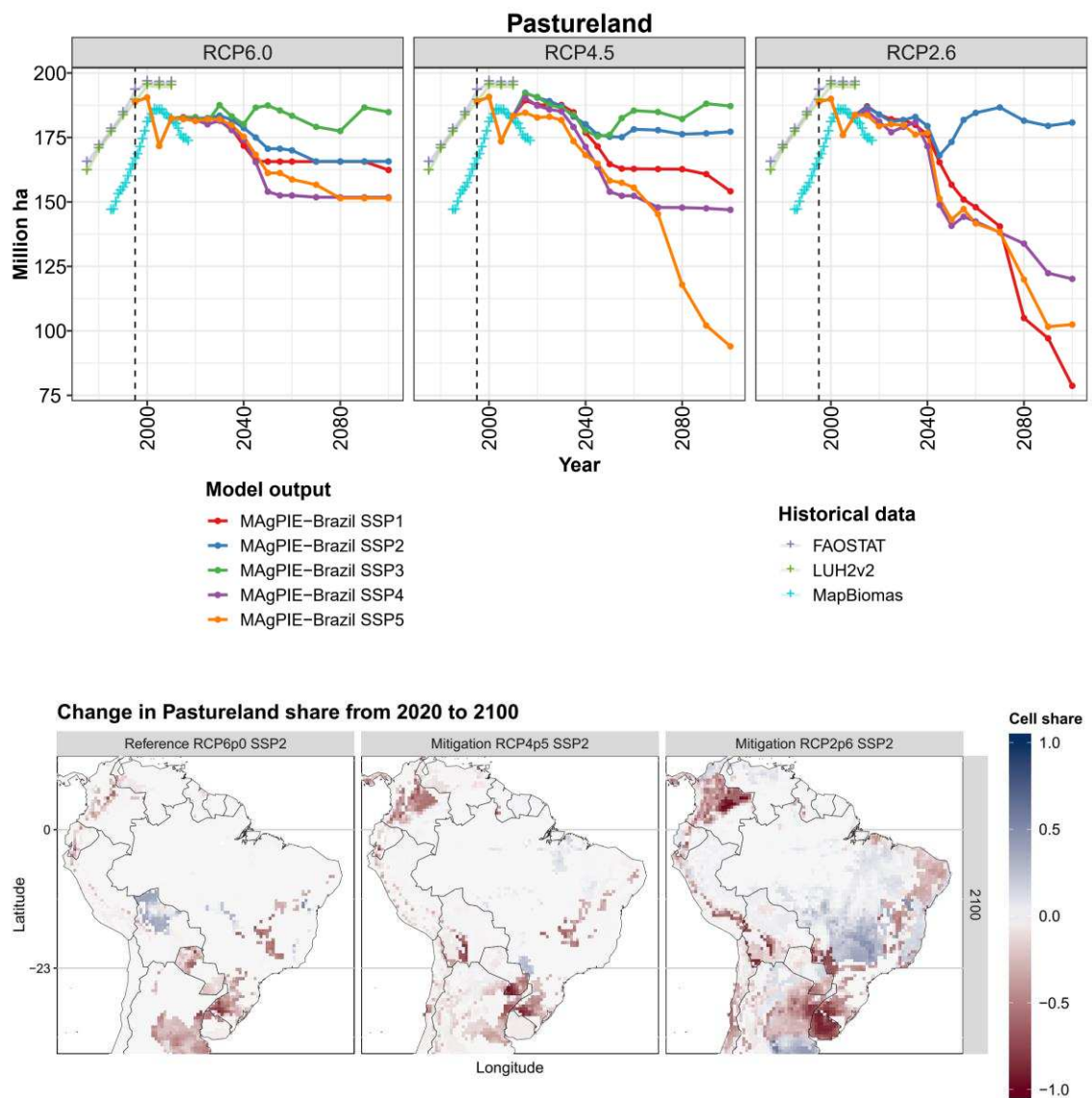


Figure 9. Brazilian pastureland and change in pastureland from 2020 to 2100.

MAgPIE’s pastureland projections (Figure 9) present a negative spike from 2000 to 2005 that disconnect projections from historical data. Low yield pastures in South

(Figure A5, Appendix 2) motivate the abandonment of pasture in the region, which can cause forest stock to stay stable while historical data keeps decreasing in the same period in roughly constant forest stock in the same period (Figure 5). The decrease in pastureland is of about 15 million ha and it is partially compensated immediately after. The projections after 2010 do not present any similar spike and follow a decreasing pathway. Pastureland has already peaked in all RCP-SSP scenarios, except RCP6.0-SSP3, and a robust decrease is expected in most of the scenarios.

Pastureland in RCP2.6-SSP2 presents a particularly interesting dynamic. In this scenario, pastureland in Brazil decreases from 2035-2045 (15 million ha) and then restarts to increase from 2045-2070 (20 million ha). From 2020 to 2045, pastureland share decreases in the South, Southeast, and Northeast but remain unchanged in Center-West (Figure A6, Appendix 2). From 2045 to 2100, pastureland share increases in Center-West, Southeast and MATOPIBA (Figure A6, Appendix 2). In addition, cropland decreases from 2045 to 2055 (Figure 8), which also indicates conversion from cropland to pastureland. At the international level, pastureland decreases in all regions except Europe and Food/Feed cropland decreases in all regions. On the other side, from 2050 onward, managed forestland increases for all regions (except Europe and USA) and bioenergy cropland increases more for the other regions than for Brazil from 2040 onwards. Concomitant to all these international dynamics, Brazil is the only region where pastureland increases. The geographical dynamics of the period demonstrates afforestation and bioenergy crops taking over pastureland in South America. Forest share increases in Colombia and Ecuador (Figure 5) and bioenergy crops share increases in Uruguay, Argentine and the South of Brasil (Figure 8) in the same spots where Figure 9 presents decreases in pastureland share. The increasing in Brazilian pastureland after 2045 may be a consequence of the increasing demand for bioenergy crops, which starts to increase rapidly in Brazil after 2040 (see Figure 4), and international pasture relocation to Brazil. Bioenergy crop and afforestation may take over less productive pastureland and push pasture to highly productive areas, such as those with increased pastureland share in the Center-West Brazil (Figure 9).

### **3.1.5. Production, yields, trade, and price**

Figure 10 presents production of Food/Feed crops, ruminant meat and bioenergy crops. MAgPIE's Brazilian crop production perfectly matches FAOSTATS historical data. The crop productions peaks at 2050 in most of the RCP-SSP scenarios. With the exception of SSP3 scenarios, Brazilian food/feed crops production pathways are

similar in all RCP-SSP scenarios and reach 2100 with between 375 Mt DM and 665 Mt DM. Ruminant meat projections disconnect from historical data in the initial years due to the pastureland decrease observed in Figure 9. It peaks between 2035 and 2040 in most of scenarios and then decreases. Ruminant meat production decreases from 2040 onward in most of the scenarios as following the decreases in Brazilian food and feed demand (Figure 4). Bioenergy crop production follows a path similar to the Brazilian demand for it. In general, Figure 10 depicts the role of demand in defining production, as it follows roughly the same path presented in Figure 4. It is noteworthy the increasing relative importance that bioenergy crops presents related to food/feed crops in RCP2.6. In the RCP2.6-SSP2, for example, Food/Feed Crop Production peaks at 700 Mt DM in 2050. Bioenergy Crop Production, by its turn, is 294 Mt DM in 2050 and peaks at 1238 Mt DM in 2090.

Figure 11 presents crop and pasture yields. SSP1 scenarios depict socioeconomic features of a sustainable development world with lower demand, which requires less intensification. Mitigation scenarios, by its turn, imply higher land use for afforestation and for bioenergy crops, which means higher land competition and relative advantage to invest in technological changes when comparing to No-Mitigation. However, as explained in section 2.3.2, investments in technological change to increase yields as a response to land scarcity is only captured by crops, which have an endogenous implementation (DIETRICH et al., 2014). Pasture yields, by its turn, can only increase as a response to higher demands and this is depicted by the results in Figure 11. Pasture yield follows a path similar to feed demand (Figure 4) and present high productivity in SSP2 and SSP3, the ones with higher food and feed demand. As the model can only respond to land scarcity with more pasture expansion, it is possible that the decreases in pasture yields are also due to land expansion towards low productive areas. Most of the pasture yield pathways have already peaked and shall follow a decreasing path now on, but this can be more a model artifact than a robust result.

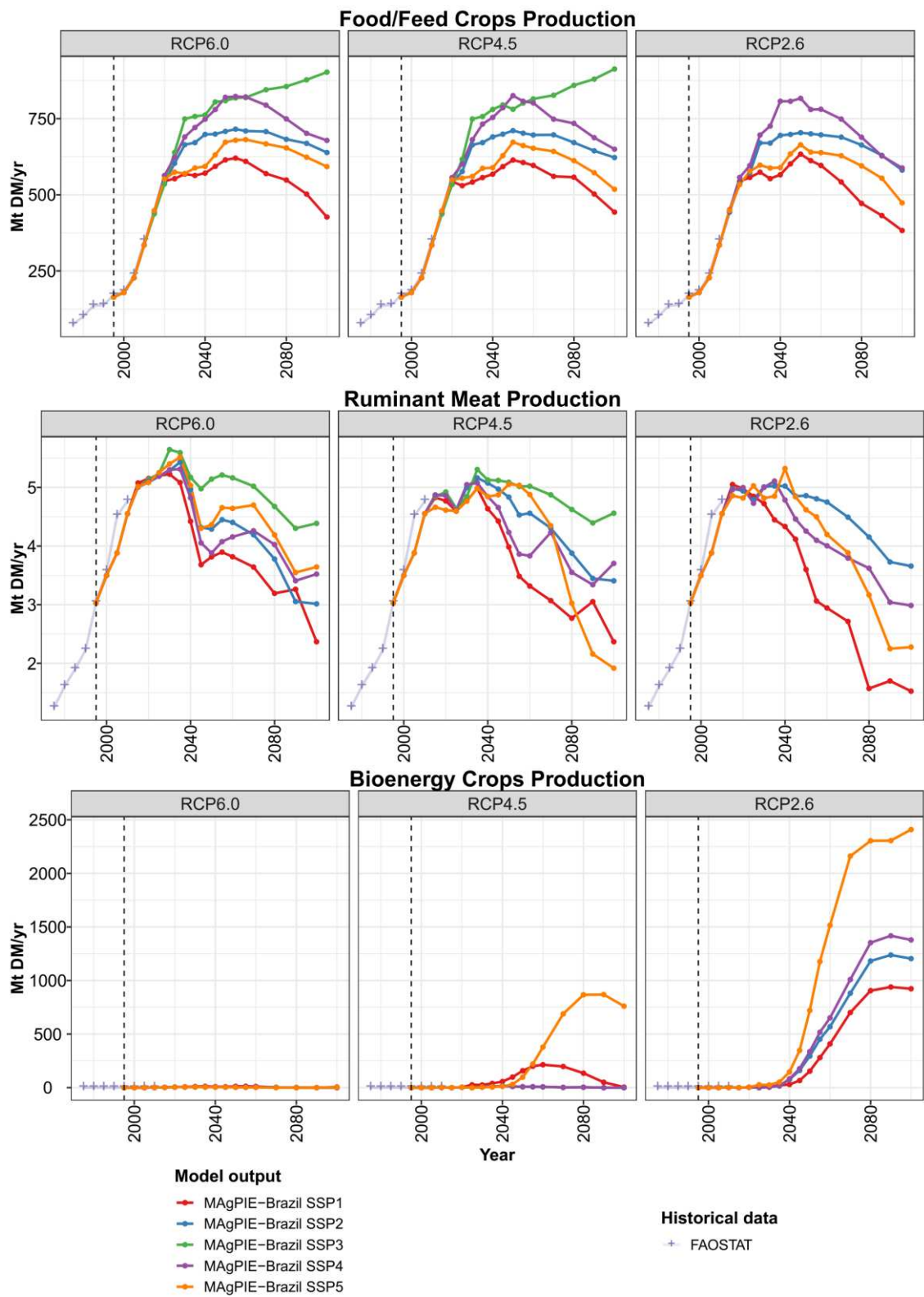


Figure 10. Brazilian food/feed crops, ruminant meat and bioenergy crops production.

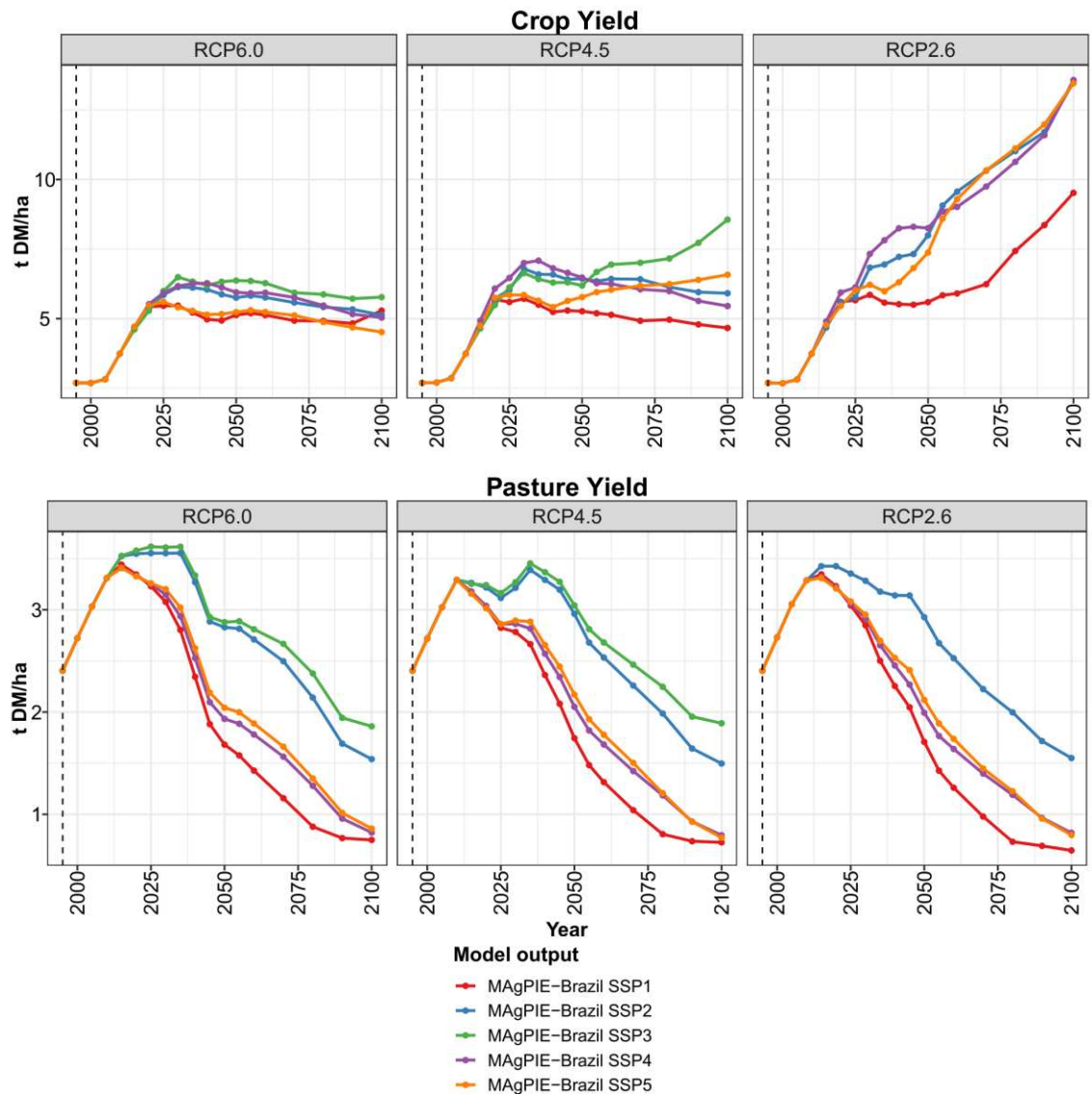


Figure 11. Brazilian crop and pasture yields.

Figure 12 presents how Brazil would benefit and disadvantage from climate change from different perspectives. Brazilian Net-Trade increases as moving towards RCP2.6 mainly due to bioenergy crops exports (Figure A7, Appendix 2), which accounts for 60% of Brazilian exports in RCP2.6-SSP2 in 2100 and 83% in RCP2.6-SSP5. The structural changes related to RCP2.6 imply that Brazil, China, Europe and the USA become high producers and exporters of bioenergy crops (Figure A8, Appendix 2). On the other side, Brazilian food prices increase exponentially for most of the SSPs in the RCP2.6 and much more than compared to other MAgPIE-Brazil's regions in this RCP (Figure A9, Appendix 2). The land competition between food/feed crops, pastureland, and bioenergy crops pushes up food prices especially in Brazil, as the country is an important producer of all these products. In RCP2.6-SSP2, as presented in Figure 9, such global competition pushes pastureland back to Center-West after 2045 and this is the

scenario with the highest food price index increase. The RCP2.6-SSP1, on the other side, presents the lower increase in Brazilian food price in RCP2.6, although it has one of the lowest Net-Trade. As the price elasticity of demand for major food categories is inelastic (ANDREYEVA; LONG; BROWNELL, 2010), it is likely that the increasing prices affect the poorest the most, as they have to spend a higher share of their income in food products.

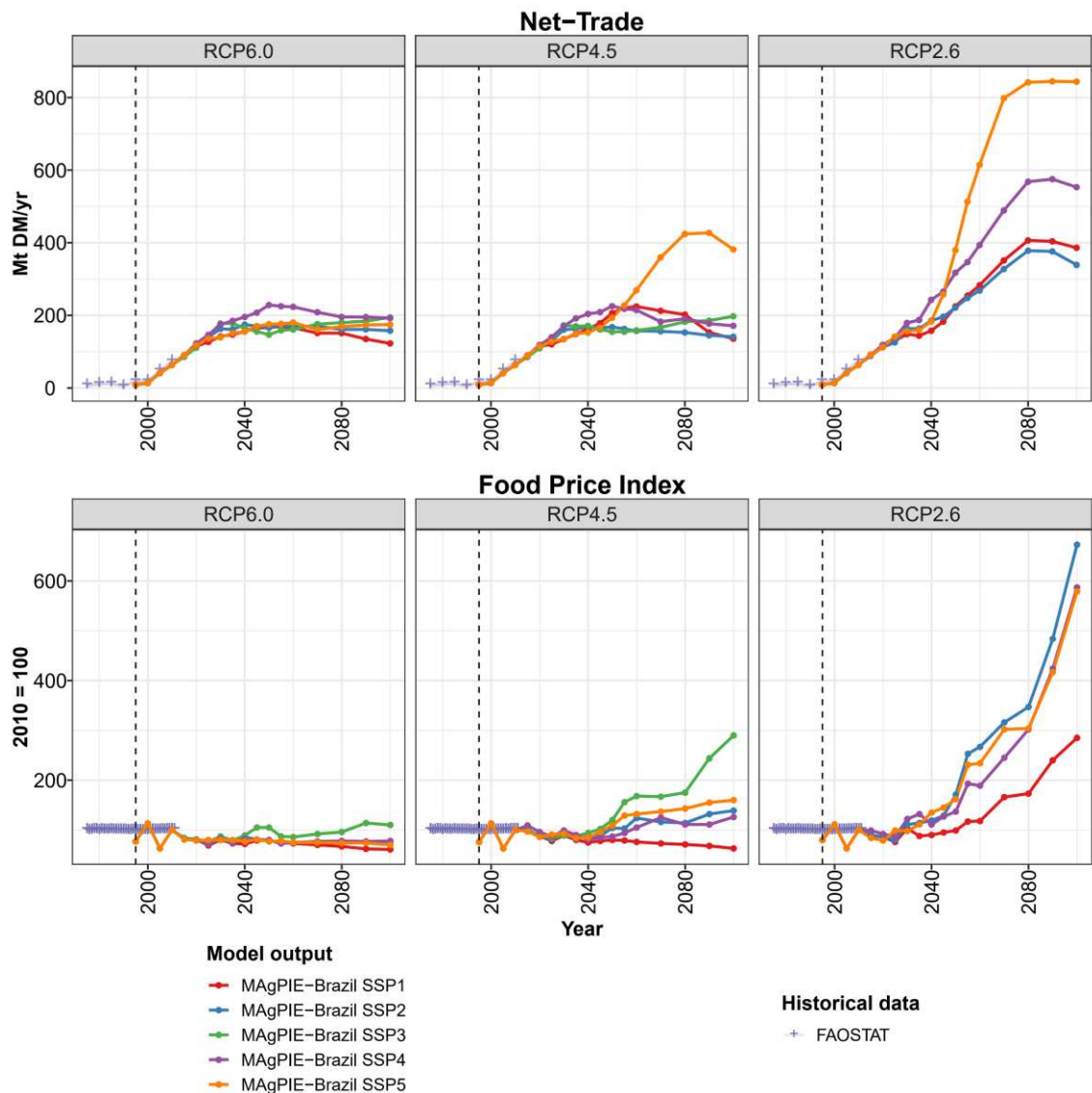


Figure 12. Brazilian net-trade and food price index.

In an overview, Figure 12 depicts orthogonal effects even in the mitigation scenarios: from the perspective of the market, there are opportunities for exports; from the perspective of the consumer, the increase in food prices has to be dealt with. In the end, the described effects from Figure 12 have to be set in the perspective of pasture yields, which would be higher if the model were able to account for intensification as a reaction for land scarcity and not only to increase cattle density as a response to increases in demand. If the model invests more in pasture intensification, it would require less

pastureland and, therefore, it would soften the effects that land competition has on food prices.

### **3.1.6. Summary of results**

- Brazilian land use evolves in diverse pathways depending on the socioeconomic and biophysical assumptions.
- In most of the scenarios, pastureland decreases from 2030 onwards, cropland increases up to 2040 then stabilizes or decreases and natural land depletion stops around 2040.
- Cropland expansion takes over abandoned pastureland in the South and Northeast.
- The emergence of a global biofuel market brings opportunities for Brazil to produce and export bioenergy crops.
- Mitigation scenarios present increasing exports (mainly bioenergy crops), increasing food price and more crop intensification.
- In RCP6.0 and RCP4.5, Brazilian CO<sub>2</sub> cumulative LUC emission stabilizes after 2050, except RCP6.0-SSP3 that keeps increasing.
- In RCP2.6, Brazilian CO<sub>2</sub> cumulative LUC emission stabilizes from 2015 onwards and massive CO<sub>2</sub> sequestration occurs from 2050 onwards.

### **3.1.7. Discussion**

Brazilian land use evolves in diverse pathways depending on the socioeconomic and biophysical assumptions, which are important drivers of demand. Demand varies widely across the SSPs. Food and feed demand are higher in SSP3 and lower in SSP1 in Brazil and globally (Figure A2 and A3, Appendix 2). High variability in global demand in diverse SSPs has also been assessed by Integrated Assessment Models, which include other dynamics than land use (POPP et al., 2017). High Brazilian demand in SSP3 scenarios posit opportunities for production that result in pressure for deforestation, while the low demand in SSP1 scenarios incentivizes abandonment of agricultural land and regrowth of natural land. Food and feed demand in SSP2 is lower than in SSP3 and higher than in the others. The pathway of population projection in SSP2 is the closest to the Brazilian official projection (IBGE, 2019), enhancing its reliability. Food and feed demand in RCP2.6-SSP2 is the highest because RCP2.6 is infeasible with the socioeconomic assumptions of SSP3. By one side, this scenario presents high pressure

for deforestation in RCP2.6, but on the other side, the Carbon Emission Prices disincentive deforestation. As a result, RCP2.6-SSP2 is the one where relatively high socioeconomic demands are concomitant with environmental sustainability, consolidating two diverse development aims. However, the scenario where both aims are met implies the highest and fast increasing Brazilian food prices. This increase is motivated by boosting land competition due to afforestation and bioenergy production. Large-scale bioenergy production without complementary measures may incentive adverse side effects to deforestation, CO<sub>2</sub> emissions from LUC and food prices (HUMPENÖDER et al., 2018). Therefore, following RCP2.6-SSP2 will require policies to soften the undesired increase in food prices, such as enhancing technological changes investments. Similar investments were done before, in the 1960s and increased soybean yields in the 1970s (PASTORE; DA SILVA DIAS; DE CASTRO, 1976). The increase in TFP (GASQUES; BACCHI; BASTOS, 2018) from the 1970s to the 2000s and agricultural intensification from 1990 to 2012 (DIAS et al., 2016) have the potential to reduce production cost and to allow for reducing food prices in all scenarios.

Production and land-use pathways have been assessed in previous Brazilian research in SSP2 by the impacts of the compliance of the Forest Code. However, these studies had no assessment of the effects that diverse biophysical and socioeconomic assumptions could have (CAMARA et al., 2015; SOTERRONI et al., 2018a) or presented a limited set of biophysical scenarios (ZILLI et al., 2018). By evaluating 14 different RCP-SSP scenarios, the present research demonstrates the diversity of Brazilian production, land use, food price, and trade pathways. In a general overview, cropland production increases up to 2050, ruminant meat production increases up to 2035 and bioenergy crops production starts increasing only in the mitigation scenarios, from 2040 onwards.

Cropland expansion to the Northeast in SSP2 occurs in all RCPs from 2020 to 2100, mainly in Caatinga. This result is similar to GLOBIOM-Brazil's result, which projects cropland expansion towards Northeast, mainly in MATOPIBA, from 2010 to 2050 in SSP2 (SOTERRONI et al., 2018a). The divergence in the focus of cropland expansion in both studies can be because MAgPIE assumes considerably reduced deforestation in Legal Amazon, whose area partially overlaps MATOPIBA (Figure 3). The dynamics projected by MAgPIE-Brazil may enhance regional development but raise environmental concerns. This region is historically less developed than the South, Southeast, and Center-West and the agricultural expansion there brings economic opportunities. Moreover, cropland expansion takes over other land and abandoned

pastureland, which implies less Carbon emission than if it were forestland. On the other side, the region has been under water stress and water value may increase in the next decades (ALCOFORADO DE MORAES et al., 2018). Even though this cropland expansion may bring economic opportunities at relatively less Carbon emission, the long-term impacts of water demand in a water-stressed area are able to offset such benefits. More research, however, is necessary to understand how water stress would affect the local economic development.

Cropland expansion to the South in SSP2 is mainly due to rainfed maize production in RCP6.0 and RCP4.5 and due to bioenergy grains in RCP2.6. Brazilian maize production increases roughly 60% in RCP6.0-SSP2 and RCP4.5-SSP2 from 2010 to 2050. The increase in the area of maize plantations was observed in the 1990s and 2010s (DIAS et al., 2016). Brazilian bioenergy production increased from 15.4 Mt DM in 2035 to 1250 Mt DM in 2090 in RCP2.6-SSP2. Such increase represents the establishment of a new dynamic that has not been observed before. Bioenergy exports are 250 Mt DM in 2090 in RCP2.6-SSP2 and 700 Mt DM in 2090 in RCP2.6-SSP5. Large-scale bioenergy production may be associated to increasing deforestation and CO<sub>2</sub> emissions from LUC (HUMPENÖDER et al., 2018), but bioenergy crops expansion to the South occurs over abandoned pastureland, which potentially minimizes such effect. Afforestation also increases in the South region and close to the bioenergy crop plantation. However, afforestation and bioenergy crops increase in this region is likely due to the unusual low pasture yields there used as input for MAgPIE, as presented in Figure A5 in Appendix 2. Further research is required to conclude whether or not the low pasture yield used as input is reliable. If so, MAgPIE-Brazil's result indicates an opportunity of sustainable usage of these new forest areas, extending the range of economic activities in the South. In addition, land competition there could be one reason for the extreme increase in food prices observed in RCP2.6-SSP2.

Agricultural land use may remain as an important economic activity in Center-West in the next decades. The region experienced agricultural extensification over decades due to maize and soybean (DIAS et al., 2016). MAgPIE-Brazil projects expansion of pastureland (only in RCP2.6-SSP2), rainfed maize, rainfed soybean and, at a smaller scale, irrigated sugar cane during this century. Results from GLOBIOM-Brazil also indicate cropland expansion in the region (SOTERRONI et al., 2018a). Cropland dynamics in the Center-West relates more to products relocation than to deforestation of forestland. Maize and soybean expand more to the central area of Center-West while sugar cane expands to the southwestern of Cerrado biome, in the movement already

hypothesized by Carvalho; De Marco and Ferreira (2009). Future agricultural dynamics in Center-West are similar to the current ones, as it remains an important crop and livestock producer. In general, the policy challenges are to avail the region's agricultural suitability while protecting Cerrado and Amazon ecosystems. In the scenarios of SSP3, the agricultural land use in Center-West is more robust and shall require more policies to avoid depletion of natural land. In the scenarios of SSP1, agricultural land is less robust and there are future opportunities for sustainable use of afforested areas in the southern of Center-West.

Brazilian pastureland stays roughly stable in all RCP-SSP scenarios between 2010 ( $\cong$  183 million ha) and 2030 (between 188 and 179 million ha) and follows decreasing pathways afterward in most of the scenarios. This overall decrease in pastureland was depicted by GLOBIOM-Brazil in SSP2, yet, they accounted for decreases in southern Cerrado and the coast of Southeast from 2010 to 2050 (SOTERRONI et al., 2018a), while results here state no significant changes in pastureland share in these areas from 2020 to 2100. The implementation of livestock production differs in both models. GLOBIOM-Brazil accounts for different ruminant meat production systems ranging from less to more intensive while the diverse ruminant meat production in MAgPIE-Brazil can only intensify pasture production due to changes in demand (not due to land scarcity). This methodological difference can explain why GLOBIOM-Brazil presents pastureland decreases in areas where MAgPIE-Brazil has no significant changes in pastureland share. The dynamics of relocating pastureland from the South region towards the southern of Amazon biome is consistent in both models. Livestock expansion to Amazon biome has been reported in the last decades (DIAS et al., 2016) and MAgPIE-Brazil projects this dynamic between 2000 and 2030 due to high productivity pastures there. Relocation to Center-West is a different dynamic and occurs only in RCP2.6-SSP2. This is potentially driven by international pasture relocation to Brazil due to high land competition associated with this scenario. Pastureland expansion to Center-West has not been observed since 1990 (DIAS et al., 2016) and its reoccurrence would be a rupture to the current trend of reducing pasture area in the region.

In the end, MAgPIE-Brazil projections for pastureland have to be set into perspective. At first, because an unusual negative spike in pastureland between 2000 and 2005, which occur due to pasture abandonment in the South region. Secondly, because of the technological change implementation for pasture in MAgPIE that cannot capture feedbacks between land scarcity and efforts to improve pasture management. This is an important limitation because increasing cattle productivity is a required step to reduce

deforestation through the enforcement of the Forest Code (SOTERRONI et al., 2018a). Model improvements and/or other methodological approaches are therefore required to enhance the reliability of such results.

Brazilian land-use dynamics will break with the trends of depletion of natural land (forestland and other land) from 2040 onwards in all RCP-SSP scenarios, but RCP6.0-SSP3. Although this result is similar to other researches (CAMARA et al., 2015; SOTERRONI et al., 2018a), it has to be taken carefully because of the discrepancy between model results and observations. Deforestation itself stops or follow a roughly declining trajectory from 2030 onwards in most of the RCP-SSP scenarios. It is important to note that the deforestation restrictions (Brazilian NPIs) still allow for some degree of deforestation and, despite this possibility, the model finds its optimal solution with very low deforestation after 2030. The main causes for finishing deforestation are twofold. The first is the demand, especially feed demand, which is the main driving force of production and roughly stabilizes or decreases in most scenarios after 2030. The second is cropland expansion towards abandoned pastureland instead of forestland, which is a more feasible option. Zero deforestation in the next decades is a sound result from the models perspective as it occurs in most of the RCP-SSP scenarios. However, in practice, the farmer is the one to decide for deforesting or using abandoned pastureland as land for new plantations. Although MAgPIE simulates many biophysical and costs interactions at the cluster level, the full dynamic still depends on factors not captured by the model, such as land tenure and farmer's legal reserve quotas. In this perspective, MAgPIE-Brazil's zero deforestation is part of an optimal solution for the model and, therefore, provides support for policies and deeper researches aiming at it.

MAgPIE-Brazil's projection about finishing deforestation in the next decades is similar to Soterroni; Mosnier; et al. (2018) projections from GLOBIOM-Brazil, which attest for little deforestation occurring in Brazil from 2030 onwards in the case of fully enforcing the Forest Code. Deforestation in Brazil depends highly on the enforcement of deforestation mitigation measures (CAMARA et al., 2015). The full enforcement of the deforestation mitigation targets in the present research occurs from 2020 onwards, when the NPI infer the highest constraints. Even after 2020, natural land depletion remains as an optimal alternative for agricultural land use: deforestation occurs up to 2030 and depletion of other land occurs up to 2040. Brazil has committed to stop illegal deforestation in Amazon by 2030 (BRAZIL, 2015) and the results suggest that deforestation in Amazon may stop around this period. The usage of the high-resolution

deforestation monitoring (DETER-B) to identify small deforestation sites is an important instrument to enhance the accomplishment of this aim.

From the total Brazilian GHG emissions in 2016, 57.8% were accounted by the LUC sector (SEEG, 2017), which depicts the important contribution that the sector would have on the country's GHG mitigation. Brazilian CO<sub>2</sub> emissions from LUC follow a similar decreasing path as deforestation and short-term commitments guide its efforts to reduce CO<sub>2</sub> emissions. By the NPCC, Brazil committed to having CO<sub>2</sub> emissions from AFOLU sector lower than 516 Mt CO<sub>2</sub> in 2020 (BRASIL, 2009a, 2018b) and the projections here indicate the achievement of this target in all RCP-SSP scenarios (the highest value is 334 Mt CO<sub>2</sub> in RCP6.0-SSP4). By the NPCC, Brazil committed to reducing its total GHG emissions 43% below 2005 levels in 2030 (BRAZIL, 2015). Assuming this 43% GHG reduction target for the LUC CO<sub>2</sub> emissions, 5 out of the 14 RCP-SSP scenarios do not achieve the target: RCP6.0-SSP1, RCP6.0-SSP2, RCP6.0-SSP3, RCP6.0-SSP4, and RCP4.5-SSP3. Not to meet the GHG reduction targets even when the Brazilian NPIs are on means that these NPIs are not sufficient for achieving the given targets in the land-use sector. In this case, further action is necessary. The measures to reduce CO<sub>2</sub> emission from LUC include avoiding deforestation and increasing afforestation. Large-scale afforestation in MAgPIE only occurs in the RCP2.6 scenarios and after 2040 and it is too late to help to achieve Brazilian mitigation targets for 2030. Measures to reduce deforestation, by the other side, would limit pastureland expansion towards potentially high productive areas (in the Amazon). Complementary policies aimed at recovering degraded pastures would promote pastures rotation by increasing pasture productivity of abandoned pastures, creating an alternative for pastureland expansion.

Brazilian crop demand increases up to 2050 and global crop demand increases up to 2070 in most of the scenarios (Figure A10, Appendix 2). Cropland expansion over abandoned pastureland would be smaller if crop intensification were stronger. In this case, more abandoned pastureland can be subject to afforestation policies such as depicted in RCP2.6. In this RCP, intensification becomes more feasible because agricultural expansion is more costly due to Carbon emission prices. However, other alternatives such as financial credit for machinery and enhancing technical training for the producers would also incentivize intensification. Technological change is a current investment expected to pay off in the long-term, taking governance into account (represented by interest rates). A solid macroeconomic dynamic reflects in a higher wiliness for long-term investments, such as technological change. Land competition between food/feed crops and bioenergy

crops increase food prices in RCP2.6 scenarios and higher yields would weaken this competition. Low interest rates depicted in SSP1 scenarios incentivize technological change investments in SSP1 more than in other SSPs. Socioeconomic changes associated to SSP1 can be an alternative to soften the effects of land competition that occurs in the presence of robust bioenergy markets.

High bioenergy demand incentivizes land competition but also posits the opportunity for Brazil to get into a global bioenergy crops market. In RCP2.6, bioenergy crops production is at least 923 Mt DM in 2100 and net trade is at least 240 Mt DM. Bioenergy markets in RCP4.5 depend highly on the SSP assumptions, as there is considerable demand only on RCP4.5-SSP1 and RCP4.5-SSP5. Brazil also remains as an important food/feed crop and livestock products producer in all RCP-SSP scenarios. Food/feed crop production increases at least 83% from 2010 to 2050 and net-trade at least 169%. Livestock products production increases at least 58% from 2010 to 2050 and net-trade at least 142%. After 2050, agricultural production stabilizes or decreases in most of the RCP-SSP scenarios. However, bioenergy market rises may support agricultural sector production after 2050 in all RCP2.6 and in some RCP4.5 scenarios. Currently, Brazilian bioenergy grains production is at a very initial stage and, in RCP6.0, it should remain like it. Policies aimed at supporting a potential transaction from food/feed to bioenergy crop production are required, especially in the South, where bioenergy is expected to expand the most.

The overall evaluation of the results indicates diverse pathways, possibilities of land expansion and land reduction, increasing and decreasing emission, diverse effects on trade, among others. The results of Brazilian land-use dynamics depicts general outlines that can orientate other research questions and methodological approaches. Even the reduction of deforestation in the next years, which only does not occur in SSP3 scenarios, presents uncertainties on how these pathways were defined. The negative spike in pastureland in initial years is a warning sign to evaluate pasture results with care, especially because of MAgPIE's limitation related to pasture yields. Moreover, it is important to understand what would have happened if it were not the Brazilian mitigation of deforestation measures. In the next section, I present and discuss the results related to the impacts of the deforestation mitigation measures in Brazil intending to contribute to the understanding of this more specific issue.

### 3.2. Impacts of Brazilian deforestation policies

In this section, I present and discuss the impacts of Brazilian mitigation policies in SSP2 by evaluating four scenarios:

- RCP6.0-Policy (no-mitigation, Brazilian NPIs for Legal Amazon/Cerrado on (henceforth Brazilian NPIs));
- RCP6.0-NoPolicy (no-mitigation, Brazilian NPIs off);
- RCP2.6-Policy (mitigation, Brazilian NPIs on);
- RCP2.6-NoPolicy (mitigation, Brazilian NPIs off).

I present the following outputs for Brazil, other regions and globally: natural land, CO<sub>2</sub> emissions from LUC, agricultural land, production, yields, net-trade, and food price index. I assess the impacts of Brazilian mitigation policies by comparing the outputs of Policy scenarios (which is actually a representation of reality) to the outputs of NoPolicy scenarios (which is a counterfactual representing what would have happened in the absence of the policy. MAGPIE-Brazil runs from 1995 to 2050 in a 5-year time step. The year 1995 is the starting year for analyzing the graph outputs, except for food price index, which the base year is 2010. Model validation is ensured by i) historical data in the graphs from FAOSTAT (2016), MapBiomass (2019) and LUH2v2 (2018), ii) comparisons of model outputs to observed data and to other researches; iii) the evaluation documents with all model outputs and validation data available online (AMBRÓSIO, 2019b).

#### 3.2.1. Natural Land

Figure 13 presents forestland (primary forest, secondary forest and forestry) for Brazil and for Rest of Latin America (Rest of LAM), and for Legal Amazon/Cerrado and Rest of Brazil. Brazil had 533 million ha of forestland in 1995, of which 462 million ha (86%) in Legal Amazon and Cerrado and 71 million ha (16%) in Rest of Brazil. Brazilian forestland decreases to 510 million ha in RCP6.0-Policy in 2050 and to 460 million ha in RCP6.0-NoPolicy. The enforcement of the mitigation of deforestation target would prevent a net loss of 50 million ha (10% decrease) of Brazilian forestland in the RCP6.0. The high Carbon emission prices in RCP2.6 makes afforestation an economically feasible option. Therefore, it promotes afforestation and hinders deforestation in both Policy and NoPolicy scenarios of RCP2.6. Brazilian forestland decreases to 527 million ha in RCP2.6-Policy in 2050 and to 519 million ha in RCP2.6-NoPolicy. The enforcement of the mitigation of deforestation target would prevent a net loss of 8 million ha (2% decrease) of Brazilian forestland in RCP2.6.

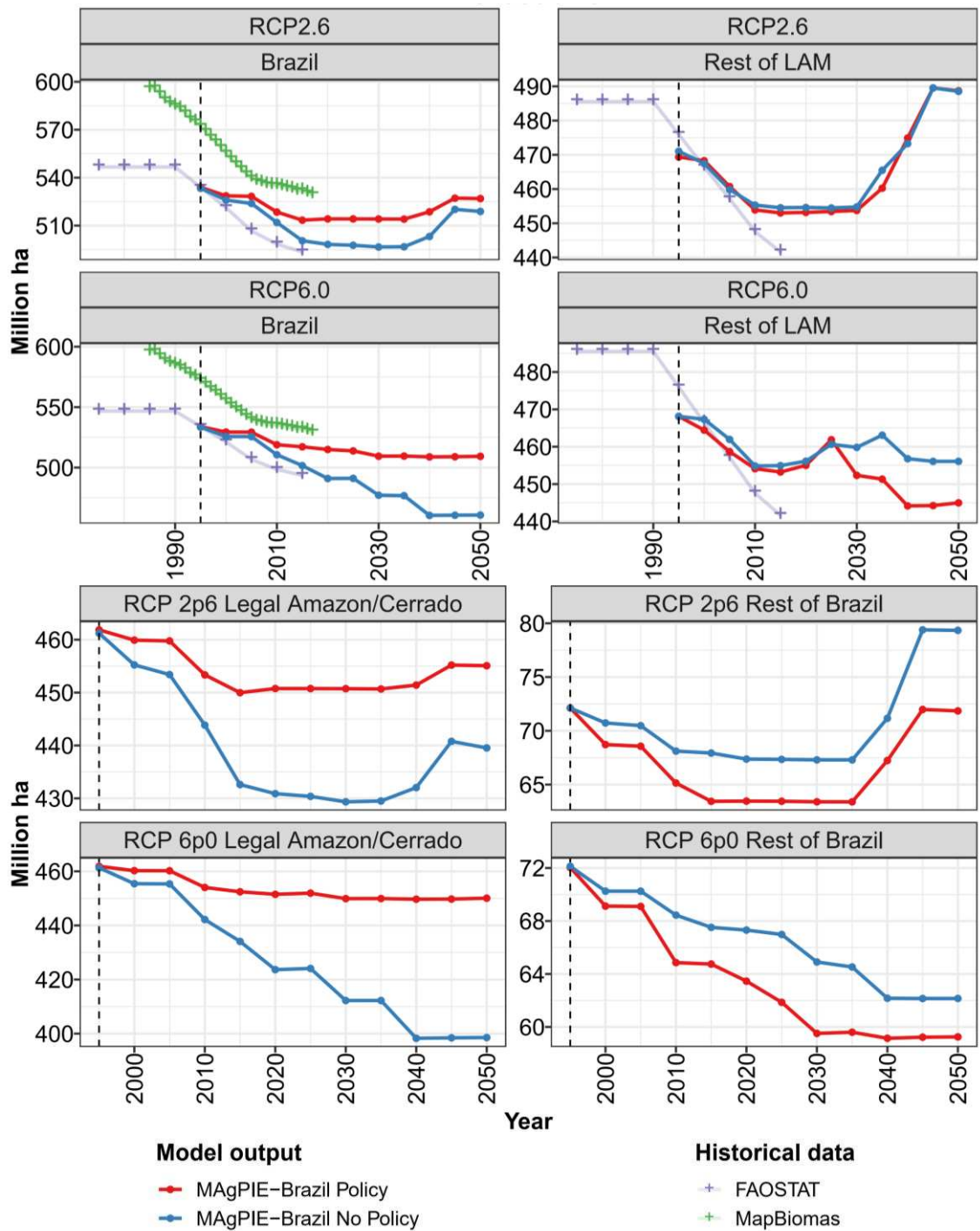


Figure 13. Forestland for Brazil and Rest of LAM, and for Legal Amazon/Cerrado and Rest of Brazil.

In 2050, Rest of LAM forestland in RCP6.0-Policy is 11 million ha lower than in RCP6.0-NoPolicy, which configures deforestation leakage effect. Although leakage exists, the policy preserves 39 million ha of Brazilian forestland more than the leakage effect to Rest of LAM in RCP6.0. There is no leakage effect from Brazil to Rest of LAM in RCP2.6. As in RCP2.6 all regions faces the same Carbon emission prices, it makes leakage useless.

The comparison of the area where Brazilian policy is applied (Legal Amazon and Cerrado) to other Brazilian areas allows evaluating deforestation leakage effect inside Brazil. Figure 13 demonstrates deforestation leakage effect from Legal Amazon/Cerrado to Rest of Brazil in both RCPs. The Leakage is smaller in RCP2.6 than RCP6.0 because of the economic incentive to afforestation in RCP2.6, however not enough to fully prevent it.

Figure 14 shows changes in forest share from 2005 to 2050. In RCP6.0-Policy, deforestation spread among the country including some areas in Cerrado, southern South, southern of Legal Amazon, the Southeast and Northeast. In RCP6.0-NoPolicy, deforestation occurs strongly in the same areas and a massive deforestation in Amazon occurs following built-in infrastructure, roads, rivers, and cities. In RCP2.6-Policy, deforestation occurs alongside with some specific afforestation sites, which makes total forestland in 2050 (527 million ha) to be almost at the same value as in 1995 (533 million ha), as presented in Figure 13. In RCP2.6-NoPolicy, deforestation occurs in all the regions and especially in Amazon, but there are some specific afforestation sites. In the end, total forestland in 2050 (519 million ha) is almost the same as in 1995 (533 million ha), as presented in Figure 13.

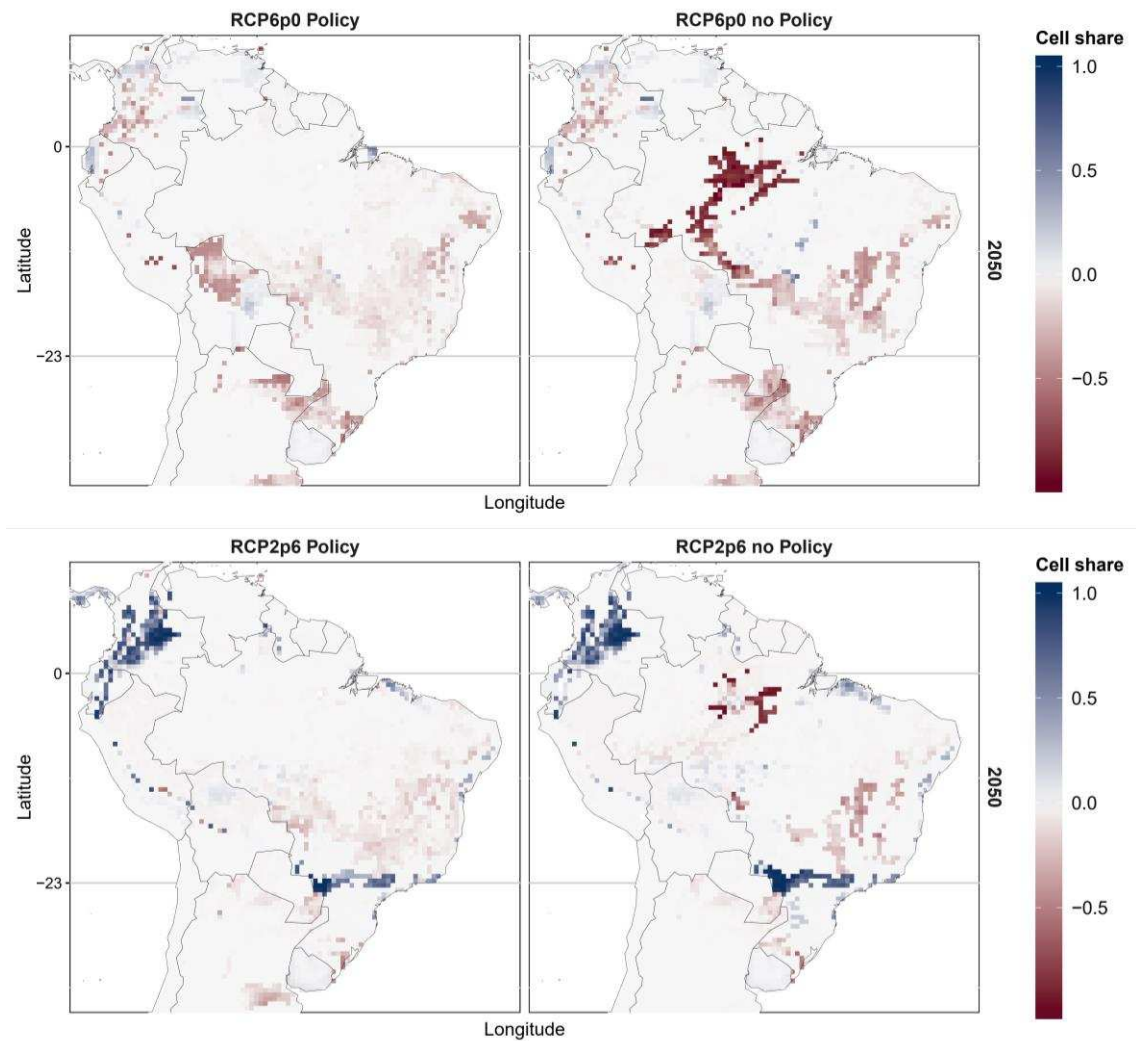


Figure 14. Change in forest share from 2005 to 2050.

Figure 15 presents results for other land, which occurs Pantanal biome (wetlands), Caatinga biome (xeric shrubland) and in MATOPIBA. Brazil had 55 million ha of other land in 1995, of which 16 million ha (29%) in Legal Amazon and Cerrado and 39 million ha (71%) in Rest of Brazil. The policy protects forestland and it potentially relocates agricultural activities over other land. As expected, Brazilian other land is lower in the policy scenarios than in the NoPolicy scenarios, in both RCPs, in 2050. Other land is lower in both Legal Amazon/Cerrado and in Rest of Brazil, in both RCPs, in 2050. The pathways of Policy and No-Policy scenarios for Brazil and for Rest of LAM are similar over time and end up with close values; therefore, the Brazilian policy has no impact on other land from of Rest of LAM. Figure 16 presents changes in other land share from 2005 to 2050. Other land share decreases mainly in Northeast and the effect is higher in RCP6.0 than in RCP2.6.

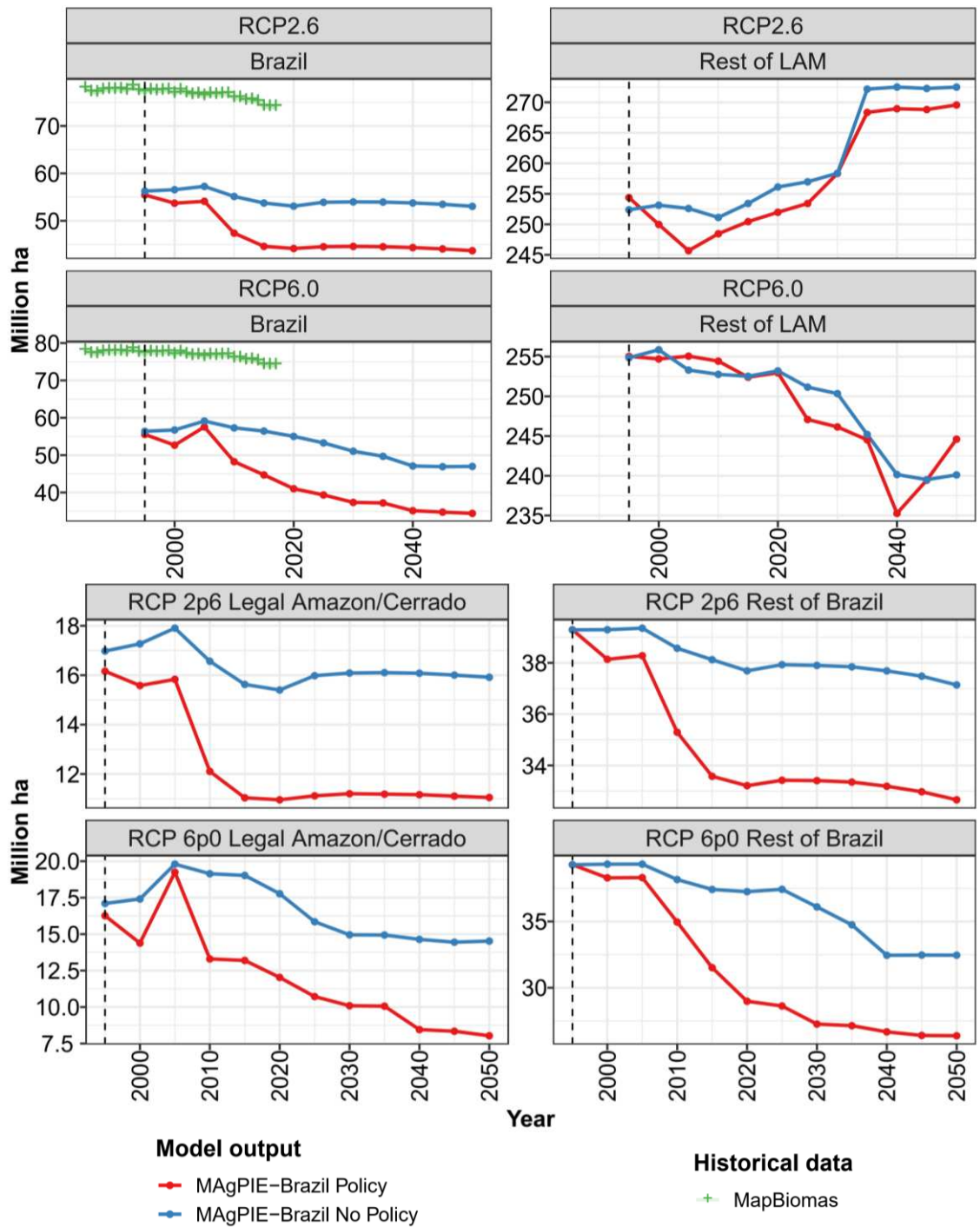


Figure 15. Otherland for Brazil and Rest of LAM, and for Legal Amazon/Cerrado and Rest of Brazil.

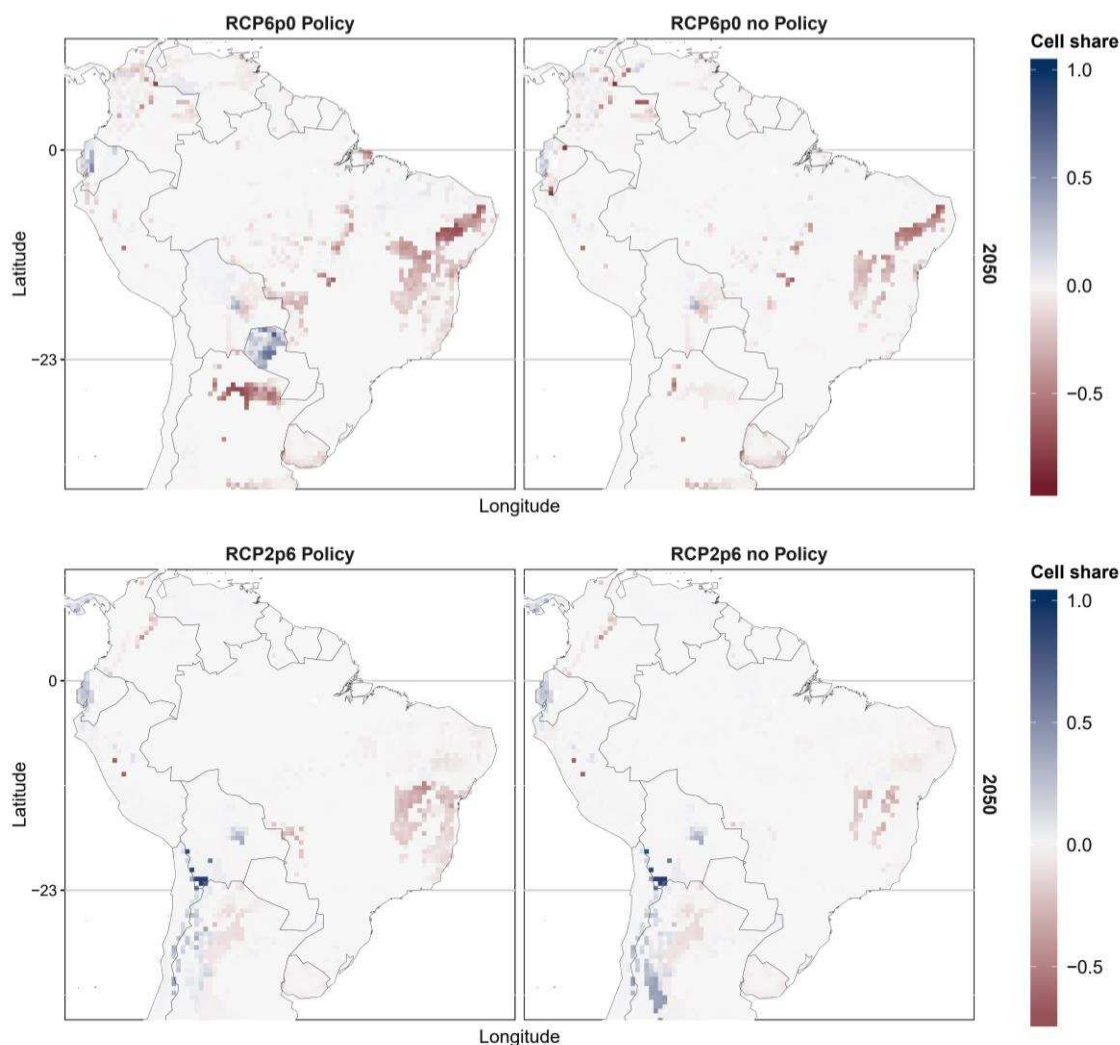


Figure 16. Change in Other land share from 2005 to 2050.

### 3.2.2. LUC CO2 Emissions

Figure 17 presents LUC CO<sub>2</sub> emissions in Brazil, Rest of LAM, and Global (World). Differently from the previous figures in this subsection, I present the results for all RCPs and Policy scenarios for one region in one graph. Each scenario has a specific color on the graphs: RCP6.0-Policy is red, RCP6.0-NoPolicy is blue, RCP2.6-Policy is green and RCP2.6-NoPolicy is purple. Emissions pathways in RCP6.0 have no overshoot and keep increasing during the whole period. Brazil accumulates 14.3 Gt CO<sub>2</sub> emission in RCP6.0-Policy (red line) from 1995 to 2050 and 34 Gt CO<sub>2</sub> emissions in RCP2.6-NoPolicy (blue line). The enforcement of the deforestation mitigation target would prevent a net emission of 20 Gt CO<sub>2</sub> (58% decrease) in the RCP6.0. Emissions pathways in RCP2.6 follow a roughly stable pathway from 2020 onwards. Brazil accumulates 9.2 Gt CO<sub>2</sub> emission in RCP2.6-Policy (green line) from 1995 to 2050 and 16.7 Gt CO<sub>2</sub> emissions in RCP2.6-NoPolicy (purple line). The enforcement of the mitigation of

deforestation target would prevent a net emission of 7.5 Gt CO<sub>2</sub> (45% decrease) in the RCP2.6.

Emissions leakage effect occurs from Brazil to Rest of LAM in both RCPs. Leakage occurs due to the relocation of agricultural activities that promotes depletion of natural land in the areas where they are settled. The most pronounced effects are cropland relocation to forestland in northern Argentina (Figure 19) and pastureland relocation to northern Bolivia (Figure 21). This relocation occurs in the same spots where Figure 15 depicts decrease in forest share, indicating CO<sub>2</sub> LUC emissions due to deforestation. Leakage emissions in other regions (besides Rest of LAM) minimize the overall effect of the Brazilian policy at the global scale. The graph in World RCP6.0 shows that the Policy scenario line (red) remains slightly below the No-Policy (blue) during most of the period, but suppress it from 2040 onwards. Therefore, the leakage effect suppresses the emission reduction obtained in Brazil due to the deforestation policy in the last time steps. In 2050, total world accumulated emission in RCP6.0-NoPolicy is 1 Gt higher than RCP6.0-Policy. The graph in World RCP2.6 presents the Policy line (green) below the No-Policy line (purple) for the whole period, indicating a global emission reduction. In 2050, total world accumulated emission in RCP2.6-Policy is 4 Gt higher than RCP2.6-NoPolicy. The Brazilian policy is globally more effective in the RCP2.6 because in this one the leakage effect is minimized due to the Carbon emission prices.

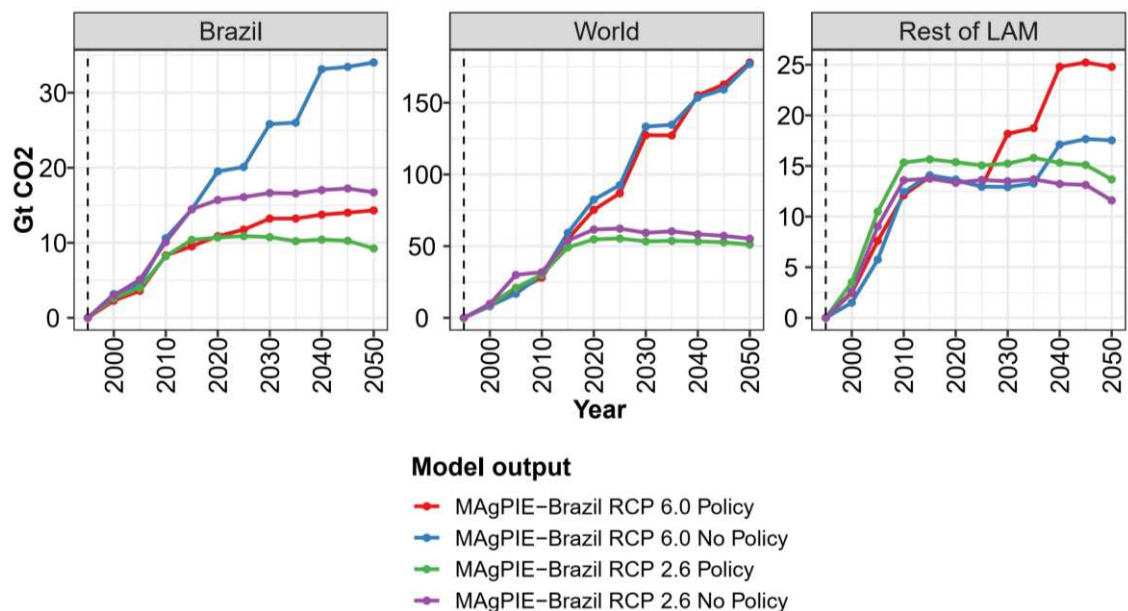


Figure 17. Cumulative LUC CO<sub>2</sub> emissions.

### 3.2.3. Agricultural Land

Figure 18 presents cropland for Brazil and for Rest of LAM, and for Legal Amazon/Cerrado and Rest of Brazil. Brazil had 61 million ha of cropland in 1995, of which 32 million ha (52%) in Legal Amazon and Cerrado area and 29 million ha (48%) in Rest of Brazil. Brazilian cropland is lower in the Policy scenarios. Cropland is 140 million ha in RCP6.0-NoPolicy in 2050 and 125 million ha in RCP6.0-Policy (15 million ha lower, 11% decrease). Cropland is 102 million ha in RCP2.6-NoPolicy in 2050 and 96 million ha in RCP2.6-Policy (6 million ha lower, 6% decrease). Brazilian policy has a restrictive effect on cropland expansion and this effect is lower in RCP2.6. The mitigation of deforestation policy implies less available land for agricultural expansion in the policy area; therefore, it is likely that the policy relocates agricultural activities elsewhere. Figure 18 depicts this dynamic from Brazil to Rest of LAM and from Legal Amazon/Cerrado to Rest of Brazil. The policy scenarios present more cropland than the NoPolicy in Rest of LAM and in Rest of Brazil. Therefore, the policy promotes cropland displacement from Legal Amazon/Cerrado to both areas (Rest of LAM and Rest of Brazil). Taking into account the decrease in other land observed in Rest of Brazil in RCP6.0 (Figure 15) it is possible that cropland takes over other land in this scenario.

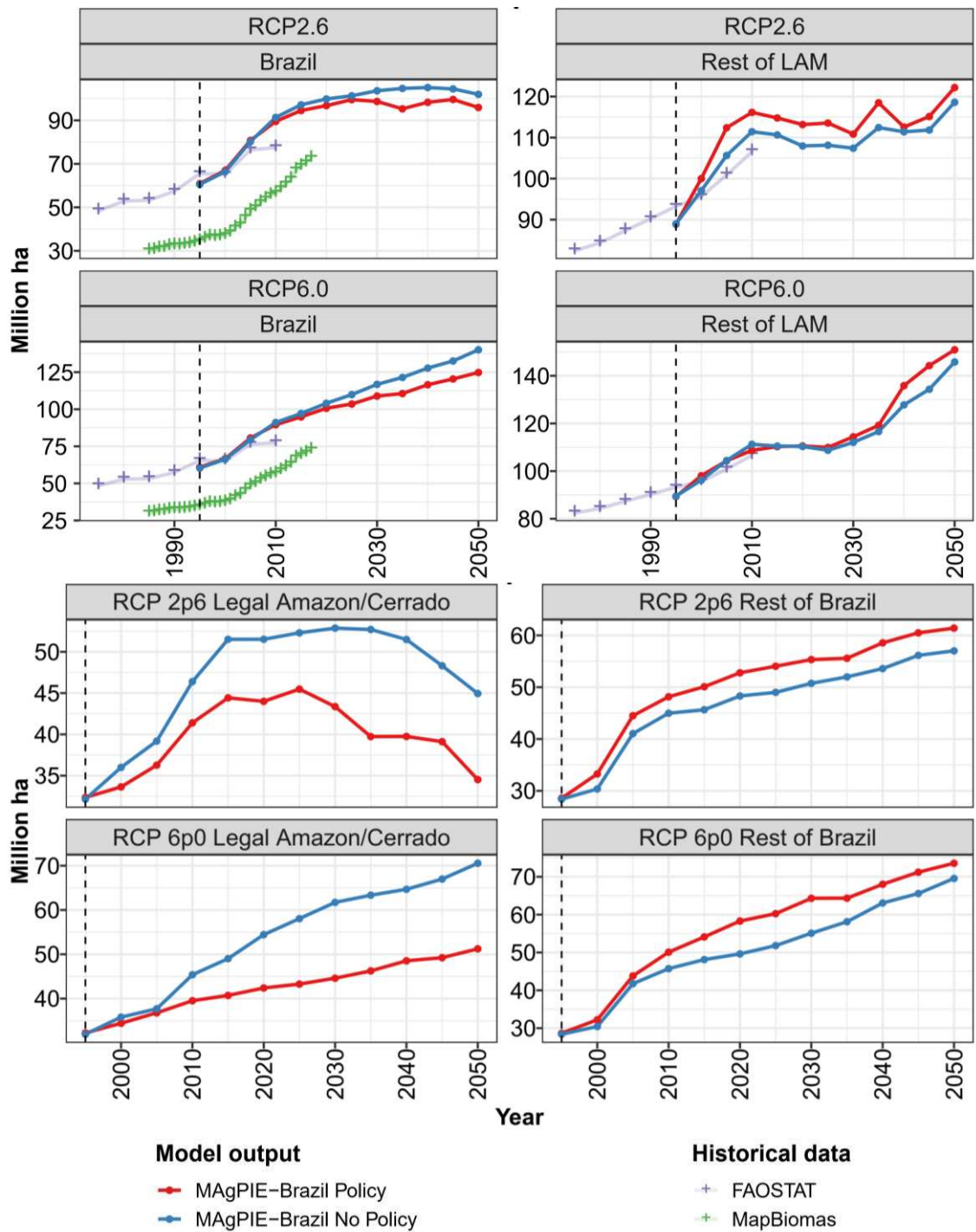


Figure 18. Cropland for Brazil and Rest of LAM, and for Legal Amazon/Cerrado and Rest of Brazil.

Figure 19 presents changes in food/feed cropland share from 2005 to 2050. In RCP6.0-Policy and RCP6.0-NoPolicy, cropland share increases substantially in South, Southeast, and Northeast, including Cerrado and part of MATOPIBA. Increase in cropland share in Northeast occurs at the same spots where Figure 15 presents decreases in other land, which enhances the hypothesis that cropland takes over other land in this area. Cropland share increases only a little in Amazon in RCP6.0-NoPolicy, which indicates that the huge deforestation observed in this area in Figure 14 is not due to

cropland expansion, but other agricultural activity. There is a mixed effect on RCP2.6-Policy and RCP2.6-NoPolicy. Cropland share presents a mixed dynamic alongside most of the country in both RCP2.6 scenarios. Despite this mixed behavior, even without deforestation policies, there is no cropland expansion to Amazon, possibly because of the Carbon emission prices penalizing deforestation. In all four scenarios, cropland share increases in the southern of the South region, eastern of Cerrado and Caatinga biome, which means cropland expansion both in mitigation and in no-mitigation scenarios.

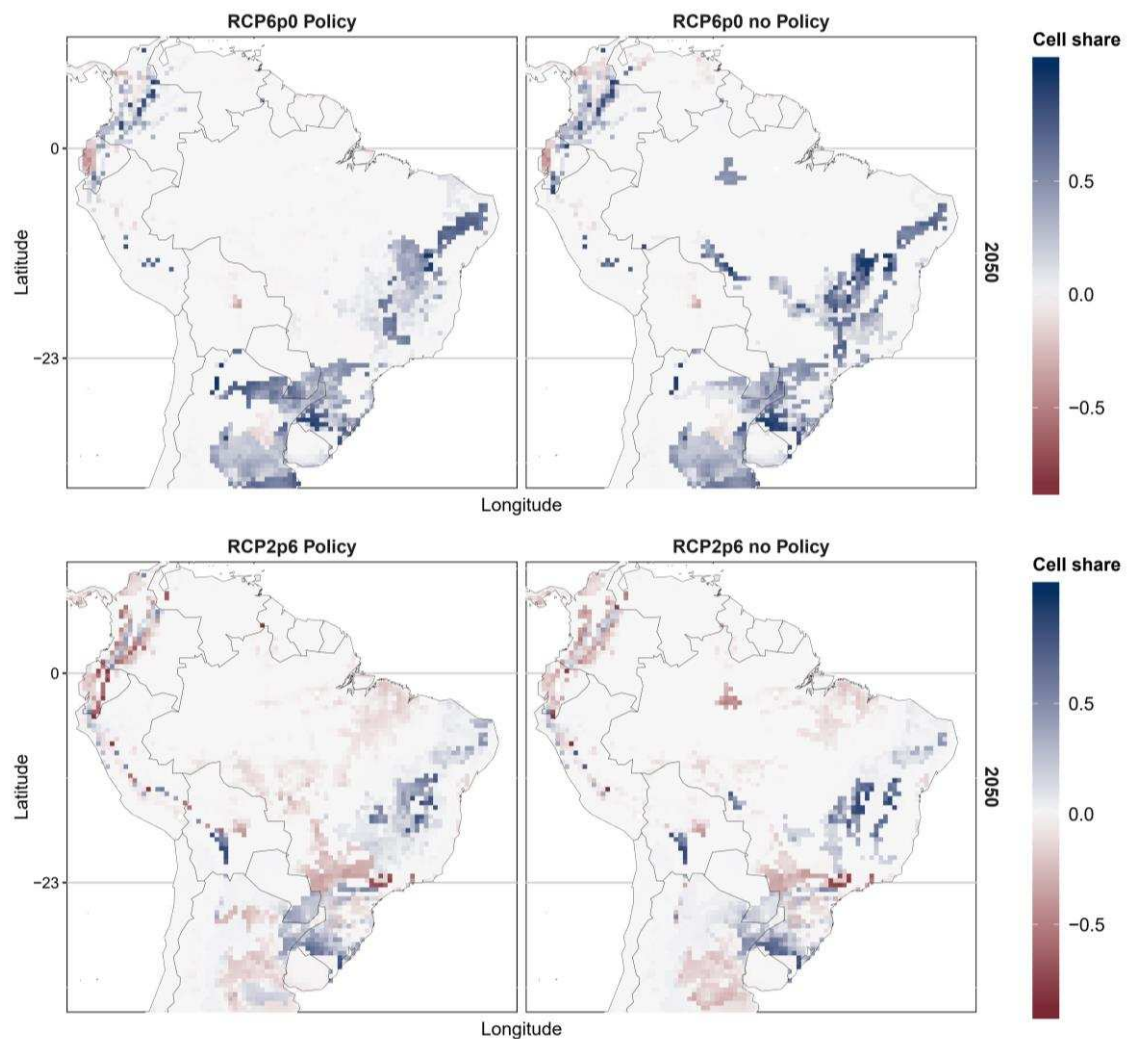


Figure 19. Change in food/feed Cropland share from 2005 to 2050.

Figure 20 presents pastureland for Brazil and for Rest of LAM, and for Legal Amazon/Cerrado and Rest of Brazil. Brazil had 189 million ha of pastureland in 1995, of which 113 million ha (60%) in Legal Amazon and Cerrado area and 76 million ha (40%) in Rest of Brazil. Pastureland decreases to 170 million ha in RCP6.0-Policy in 2050 and increases to 191 million ha in RCP6.0-NoPolicy, a net loss of 21 million ha (11% decrease) associated with the policy. The pathway of RCP6.0-NoPolicy remains above the pathway of RCP6.0-Policy for Brazil during the most of the period, indicating

that the policy is associated with lower Brazilian pastureland over time. Despite this effect, the policy relocates pastureland to Rest of LAM only at a small amount in RCP6.0. In mitigation scenarios, pastureland decreases to 172 million ha in RCP2.6-Policy in 2050 and to 165 million ha in RCP2.6-NoPolicy, a net loss of 7 million ha (4% decrease). Although there are differences in pastureland between RCP2.6-Policy and RCP2.6-NoPolicy in 2050, their pathways remain similar for Brazil during the most of the period and there is no difference in the pathway for Rest of LAM in most of the period. It indicates that, in RCP2.6, the impact of the policy on pasturelands occurs mainly inside Brazil and at a small scale. Pastureland displacement effects from Legal Amazon/Cerrado to Rest of Brazil occurs in both RCPs.

Figure 21 presents changes in pastureland share from 2005 to 2050. The dynamics for all scenarios are diverse. Pastureland share decreases in the South and in the Southeast in all scenarios and in the Northeast in RCP2.6. The abandonment of pastureland in the South and in the Northeast occurs in similar spots where cropland share increases (Figure 19), indicating that cropland takes over pastureland in those areas. Pastureland share increases in Amazon and Cerrado in all scenarios, indicating that the activity is still an economically optimal choice regardless of the deforestation restriction. In the policy scenarios, however, pastureland share is lower in Amazon and higher Center-West and some areas in the Atlantic Forest. In RCP6.0-Policy, pastureland share increases in North Bolivia in the same area as Figure 14 presents deforestation, indicating that pastureland relocation determines deforestation leakage effect there. In the NoPolicy scenarios, pastureland share increases strongly in Amazon around infrastructures sites like roads, rivers, and cities. This increase occurs in similar areas where Figure 14 presents a decrease in forestland, indicating that pastureland drives deforestation in Amazon in the NoPolicy scenarios. This dynamic is more intense in RCP6.0-NoPolicy than in RCP2.6-NoPolicy.

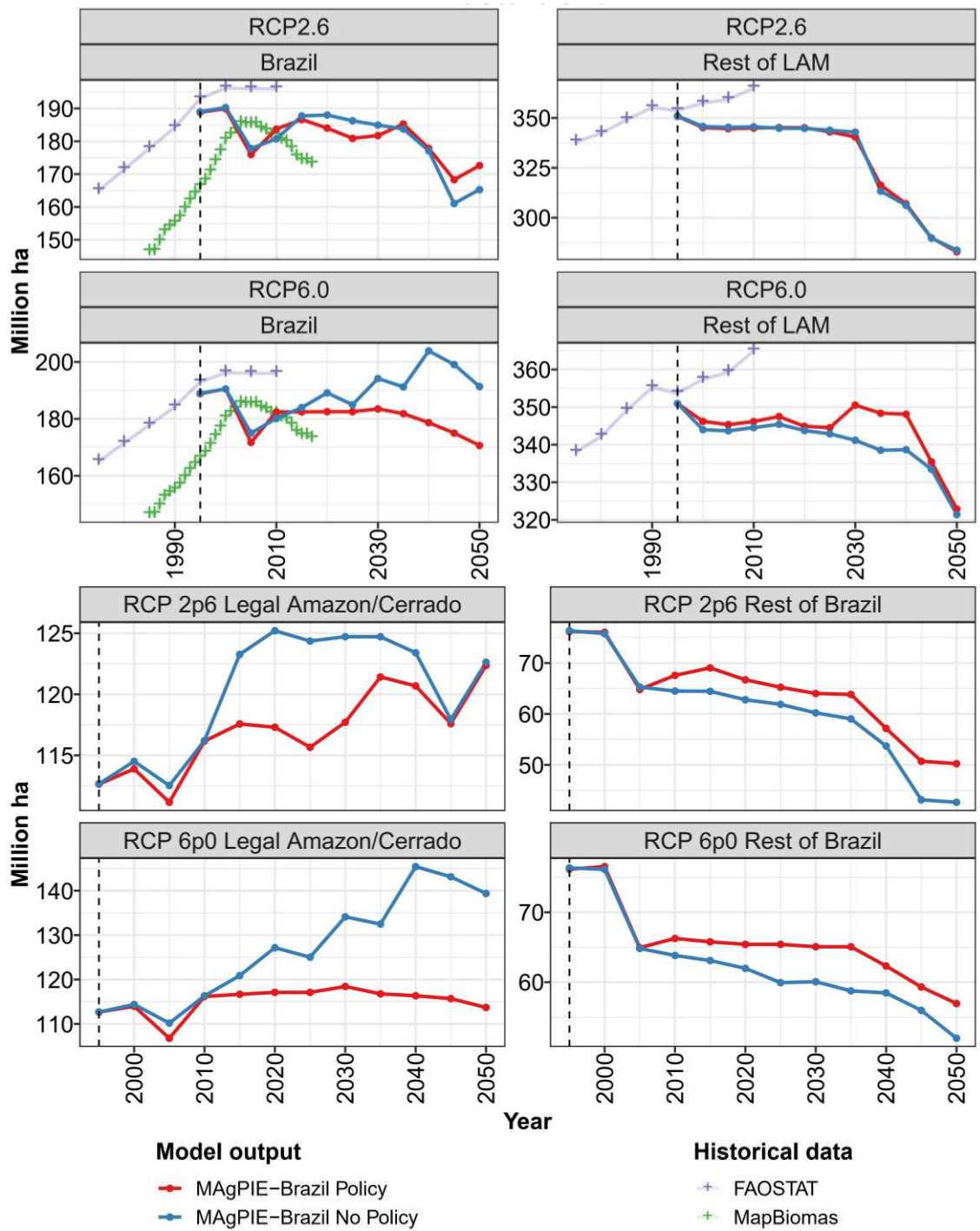


Figure 20. Pastureland for Brazil and Rest of LAM, and for Legal Amazon/Cerrado and Rest of Brazil.

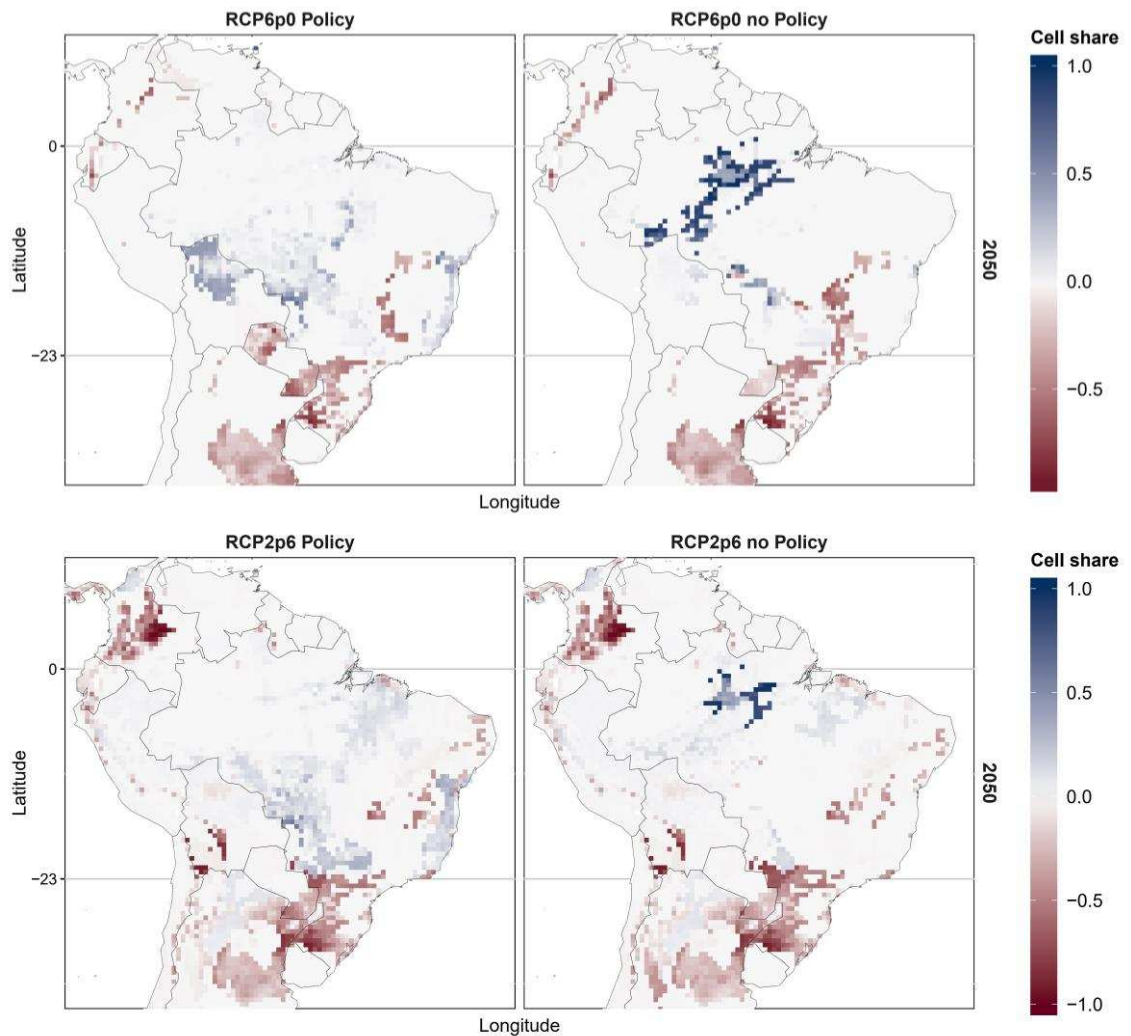


Figure 21. Change in Pastureland share from 2005 to 2050.

### 3.2.4. Production, yields, trade, and price

The effect of the policy on production, yields, trade, and price is quite small in other MAGPIE regions except for Brazil. Therefore, in this section, I present the results for RCP6.0 and RCP2.6 only for Brazil. Figure 22 shows results for production. Despite the decreasing effect that the policy has on cropland (Figure 18), food/feed crop production is affected only at a minor extent. Food/feed crop production in RCP6.0-NoPolicy is 727 Mt DM in 2050 and in RCP6.0-Policy is 708 Mt DM, a net loss of 19 Mt DM (3% decrease). In RCP6.0, the policy is associated to 11% decrease in cropland in 2050 (Figure 18) but only 3% decrease in food/feed crop production, while preventing 10% net loss of forestland (Figure 13). Food/feed crop production in RCP2.6-NoPolicy is 705 Mt DM in 2050 and in RCP2.6-Policy is 704 Mt DM, a net loss of 1 Mt DM (0.16% decrease). In RCP2.6, the policy is associated to 6% decrease in cropland in 2050 (Figure 18) but only 0.16% decrease in food/feed crop production, while preventing 2% net loss of forestland (Figure 13).

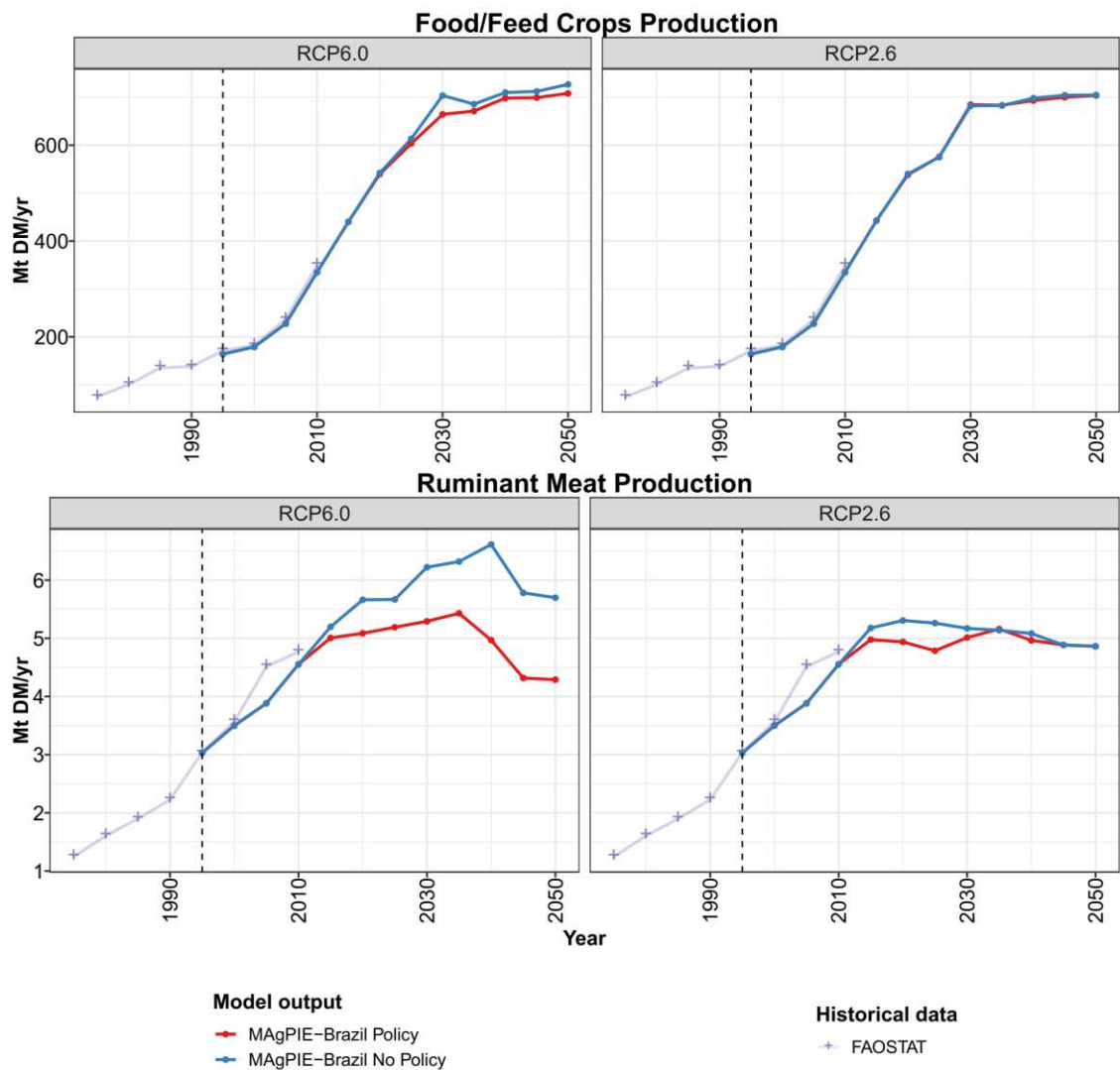


Figure 22. Brazilian food/feed and ruminant meat production.

On the other side, the policy decreases pasture production in RCP6.0, following a similar path as pastureland (Figure 20). Pasture production in RCP6.0-NoPolicy is 602 Mt DM in 2050 and in RCP6.0-Policy is 483 Mt DM, a net loss of 119 Mt DM (20% decrease). In RCP6.0, the policy is associated to 11% decrease in pastureland in 2050 (Figure 20) and 20% decrease in pasture production, while preventing 10% net loss of forestland (Figure 13). Pasture production in RCP2.6-NoPolicy is 508 Mt DM in 2050 and in RCP2.6-Policy is 507 Mt DM, a net loss of 1 Mt DM (0.2% decrease). In RCP2.6, the policy is associated to 4% decrease in pastureland in 2050 (Figure 20) and 0.2% decrease in pasture production, while preventing 2% net loss of forestland (Figure 13).

The diverse effect on crop and pasture production might be because of the different implementation that they have on the model, which do not allow pastureland yields to capture feedbacks between land scarcity and efforts to improve pasture

management. Besides this methodological limitation, the effect might have happened because of high yield land for pasture located in the policy area that has been restricted to agricultural use. If this land were used for pasture, the production would have been as higher as presented in the RCP6.0-NoPolicy. In the RCP2.6, the Policy scenario remains below the NoPolicy, but both end up at the same value in 2050. Ruminant meat production in RCP6.0 follows a path similar to pasture production in the same RCP. However, for the RCP2.6, the ruminant meat production keeps a stable horizontal pathway, which disconnects from the declining pasture production pathway in the same figure.

Figure 23 shows crop and pasture yields. The policy presents co-benefits with crop yields as Brazil intensifies more its land use in the Policy scenarios, especially in RCP2.6-Policy. As a rule, the policy deforestation constraint makes it more feasible to invest in technological change because the land outside policy area might be less productive. In the case of pastureland, the policy presents an adverse side effect with pasture yield, as it is lower in the Policy scenarios than in the NoPolicy. Pasture yields increase based on an exogenous demand-side proxy for a growth rate of cattle stocks. The policy restricts pastureland expansion in an area that is attractive for this activity (as presented in Figure 21) and in the policy scenario, the expansion to this area is restricted. In the absence of the policy, as the area has attractive biophysical conditions, the cattle density there is higher and, therefore, the pasture yields are higher as well. In the case of cropland, the Policy presents co-benefits to crop yields. Cropland expansion is mainly over abandoned pasturelands and not over the Amazon (as presented by comparing Figure 19 to Figure 21). Therefore, it is possible that the crop yield comparison between the Policy and No-Policy scenarios is not negatively affected by the policy, enhancing higher crop yields in the policy scenario.

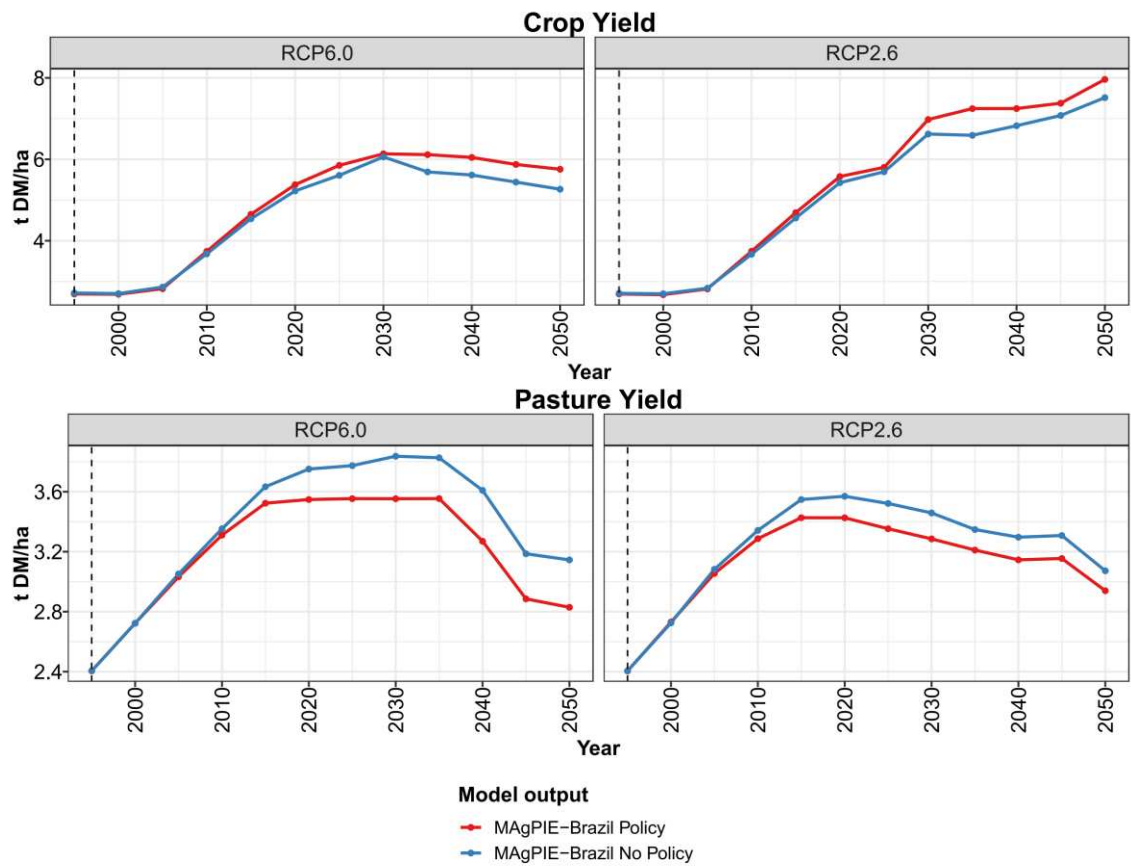


Figure 23. Brazilian crop and pasture yields.

Figure 24 presents Net-Trade and Food Price Index. On one side, the Policy scenario reduces Brazilian net-trade of agricultural goods, especially in RCP 6.0, characterizing an adverse side effect of the policy. On the other side, the Policy decreases the food price index in both RCPs, characterizing a co-benefit with the policy. As the Policy scenario restricts agricultural land use, the model endogenously decides invest in technological change in order to fulfill the demand. These investments usually pay off in the long term bringing down the production costs and, in the end, the investments reduce the food price. If the mitigation policy is evaluated from the trade balance perspective, it is an undesired result that it decreases the Net-trade. However, if the policy is evaluated form the consumer perspective, the decrease in food price is a desired result.

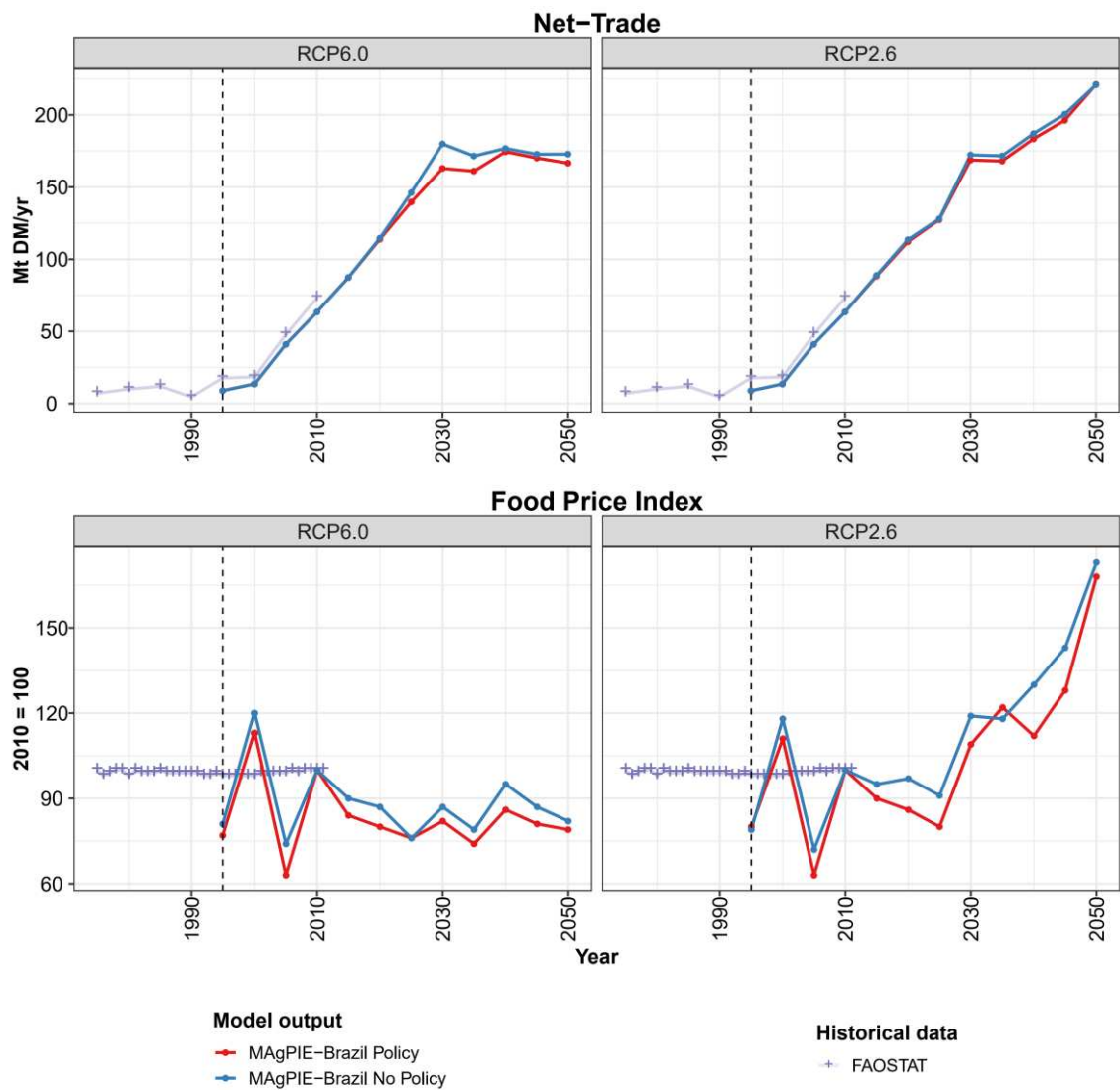


Figure 24. Brazilian net-trade and food price index.

### 3.2.5. Summary of results

- The policy implies deforestation leakage from Legal Amazon and Cerrado to Rest of Brazil and to the Rest of LAM and CO<sub>2</sub> emissions leakage effect from Brazil to the world.
- In most of the cases, the leakage effect does not fully offset Brazilian environmental gains in reducing deforestation and CO<sub>2</sub> emissions.
- Global Carbon emission prices such as used in the mitigation scenario reduce considerably the leakage effects.
- In RCP6.0, the policy prevents a net loss of 50 million ha of forestland and implies a net decrease of 36 million ha of agricultural land, compared to the absence of policy.
- In RCP6.0, the policy would prevent a net emission of 20 Gt CO<sub>2</sub>.

- In RCP2.6, the policy prevents a net loss of 8 million ha of forestland and implies a net loss of 13 million ha of agricultural land.
- In RCP2.6, the policy would prevent a net emission of 7.5 Gt CO<sub>2</sub>.
- The policy has little impact on crop production and high impact in pasture production.
- The policy presents co-benefits with crop yields and food prices and adverse side effects with pasture yields and net-trade.
- The policy reduces Brazilian agricultural emissions and its effect is higher in RCP6.0.

### **3.2.6. Discussion**

The enforcement of the deforestation mitigation targets for Legal Amazon and Cerrado restricts potential agricultural expansion that would have happened there. The comparison of the policy scenario and the counterfactual demonstrates how this effect occurred. In RCP6.0, the Policy scenario implies 15 million ha less cropland than the NoPolicy. Soterroni and Mosnier et al., (2018) found out a net decrease of around 5 million ha of cropland in 2050 due to the full enforcement of the Forest Code. Camara et al. (2015) attest for 10 million ha net decrease due to the Forest Code. Pastureland, by its turn, expands towards amazon up to 2030 in the Policy scenarios and up to 2050 in the NoPolicy. In RCP6.0, the Policy scenario determines 21 million ha less pastureland than the NoPolicy. Soterroni and Mosnier et al., (2018) found out a net decrease of around 25 million ha of pasturelands in 2050 due to the full enforcement of the Forest Code. Likewise, Camara et al. (2015) found out a net decrease of around 30 million ha of pasturelands in 2050 due to the same reasons. These studies and the present one have similar outcomes that cropland is less affected than pastureland when a new land expansion restriction is set to the model. The overall impacts of the policy in RCP2.6 are smaller. It prevents 8 million ha deforestation and implies a net reduction of 13 million ha of agricultural land. Despite the lower agricultural areas, production is only affected at a small pace, highlighting an environmentally and economically sustainable pathway. More researches using global land-use models and evaluating the impacts of deforestation mitigation policies in a 2°C warming world are required in order to evaluate the present results in perspective.

Besides influencing the total Brazilian agricultural land, the policy also relocates agricultural activities elsewhere outside the policy area. The results of the research corroborate the statements that by nationally protecting forests, interconnected

markets may displace land use and deforestation abroad (LAMBIN; MEYFROIDT, 2011; MEYFROIDT et al., 2013). Inside Brazil, Harfuch and Moreira (2012) demonstrated that creating PAs in Cerrado promotes deforestation leakage Amazon region. This result depicts a similar effect as the one from the present research, in which reducing deforestation in Legal Amazon/Cerrado relocates agriculture and implies depletion of natural land in Rest of Brazil. At the international level, cropland relocates to Paraguay, Uruguay, and Argentina. Pastureland, by its turn, would have gone deep into Amazon if it were not the mitigation of deforestation policy. In the case of RCP6.0-SSP2, pastureland relocates to North of Bolivia. In the above-mentioned dynamics, the relocation process is mainly to other land in the case of inside Brazil and to forestland in the case of Bolivia. From the perspective of LUC emissions, it is better that relocation occurs over other land than over forestland. However, cropland expansion to the Northeast would posit more pressure in an already water-stressed area (ALCOFORADO DE MORAES et al., 2018).

The relocation process occurring inside Brasil mainly towards other land reflects as lower Brazilian CO<sub>2</sub> emissions from LUC in the Policy scenario (the one that relocates agricultural activities to other land). On the other side, in the NoPolicy scenarios, pastureland goes deep in Amazon, which implies high CO<sub>2</sub> emissions. Compared to the counterfactual, the policy reduces Brazilian cumulative LUC CO<sub>2</sub> emissions in 58% (20 Gt CO<sub>2</sub>) in RCP6.0 from 1995 to 2050 and in 45% (7.5 Gt CO<sub>2</sub>) in RCP2.6. Emission leakage effect exists in both scenarios; however, it only offset Brazilian mitigation after 2040 in RCP6.0. It means that during most of the time and in both scenarios, the Brazilian mitigation policy contributes to reducing global emissions. It is important to note that Brazil is, indeed, responsible for a 20 Gt CO<sub>2</sub> in RCP6.0 mitigation compared to a counterfactual (or 7.5 Gt CO<sub>2</sub> in RCP2.6), but this value is not the Brazilian effective contribution to global mitigation. Without global regulation, leakage remains as an inevitable result of economically driven deforestation (BOUCHER et al., 2011) and offsets individual efforts to mitigate. Carbon emission prices is an example of how global isonomic regulation reduce leakage (by equally pricing Carbon emissions for all regions). This is still the usual modeling approach for achieving the associated emissions pathways, however, the current global efforts regard more to forest protection. As Carbon market has not been much used in the real world, the modeling design should advance in other more feasible ways to represent mitigation, such as the NPIs in the present research. If enough countries individually protect its own forests, agricultural relocation would go to less carbon-dense areas, such as the dynamic observed

for cropland on relocating to the South and Northeast of Brazil. Although there are still carbon emissions from non-forestland depletion, they are lower than it would have been for deforestation. Therefore, the national challenge is to develop economic feasible deforestation policies. In this way, the countries are motivated to adopt such policies to achieve individual rewards (e.g. increased yields) and not global public goods (e.g. preventing global warming), although the global public good will be an outcome of these policies anyway.

Achieving the Brazilian mitigation of deforestation targets present co-benefits and adverse side effects. The higher crop yields associated with the policy prevent climate variability and the lower food prices enhance food security. From this perspective, the policy presents socioeconomic benefits for the consumer and for the producer. These results should enhance the willingness to adopt such policies because of individual benefits beyond the global public benefit of preventing global warming. The lower pasture yields and lower net-trade are the adverse side effects related to the policy, both associated with the producer perspective. It is noteworthy that technological change implementation for crop yield increases is more robust than for pasture yield. Pasture yield do not capture dynamics on land scarcity and efforts to improve pasture management but restricting land expansion in Legal Amazon has been associated to increasing cattle productivity in some specific municipalities (KOCH et al., 2019). The lower pasture yields in the presence of the policy might be rather a model artifact coming from the different implementations than a robust result. If this is the case, lowering pasture yields may not be an adverse side effect but the result of a MAgPIE's limitation. The implementation of diverse livestock production systems and land competition as an input for determining pasture yields in MAgPIE are fundamental improvements in order to overcome the current limitations. Moreover, other researches using global land-use models have not evaluated the impacts of deforestation mitigation policies on yields, therefore the present results are not directly comparable to others.

As given by the present results, the enhancement of pasture and/or livestock productivity is required in order to soften the adverse side effects on pasture yields. Livestock intensification would be an alternative to soften the leakage effect occurring in RCP6.0 from Brazil to North Bolivia and from Legal Amazon/Cerrado to the rest of Brazil. Moreover, a 56% increase in cattle productivity over four decades is demonstrated by Soterroni; Mosnier; et al. (2018) as necessary for compiling with the Forest Code. Financial credit for investing in confined livestock and research to promote livestock related new technologies are measures potentially eligible to enhance livestock

productivity. The Low Carbon Agriculture Plan (BRASIL, 2012b) is a Brazilian policy aimed at enhancing agricultural production by using environmental sustainable measures and include enhancing Livestock-Forestry Integration and recovering degraded pastures, still, only part of the committed targets for these measures has been achieved (BRASIL, 2018c).

The overall understanding of the results is that the mitigation of deforestation policy is effective for Brazil, but its global effectiveness is offset at some degree due to leakage effects. Although Brazil is responsible for its own mitigation, its contribution for global mitigation should not be accounted as the same value because interconnected markets and displacement effects of the agricultural activities increases deforestation and emissions elsewhere. Moreover, the impacts of the policy on crop production and cropland are relatively low, which may incentivize the implementation of similar policies. On the other side, it has higher undesired effects on pasture yields, what can compromise livestock productivity.

## 4. CONCLUSIONS

This research aimed at projecting and analyzing Brazilian land-use dynamics as well as the potential global impacts of Brazilian policies to reduce deforestation, considering the effect of interconnected global markets on Brazilian LUC and the effect of Brazilian policies on international LUC. By taking advantage of MAgPIE 4.0 Modeling Framework, the research contributed to the development of MAgPIE-Brazil, which accounts for the previously mentioned dynamics and explicitly focus on Brazil and its main commercial partners. Moreover, the regionalized model allows for diverse RCPs and SSPs assumptions, which pictures a broader overview of the potential Brazilian land-use pathways and the challenges associated with each of them.

MAgPIE-Brazil's outcomes demonstrate that Brazilian land-use dynamics would follow wide and diverse pathways, both regarding biophysical and socioeconomic assumptions, which demonstrates its importance for long-term policy design. As there is no likelihood on which biophysical and socioeconomic pathway the world should follow, the research discussed 14 scenarios in order to cover a broad set of possibilities. In general, the effects of SSP1, SSP3, and RCP2.6 represent the boundaries of the pathways. Cropland expansion to Northeast may become an opportunity if care is taken relating to the region's water stress. Bioenergy crops and afforestation can represent new markets for Brazil and are the opportunity of good use of abandoned pastureland in the South. Brazil may remain as an important international player in the agricultural markets in all scenarios. All these agricultural achievements can occur concomitant to decreases in deforestation in most of the scenarios. It demonstrates that Brazil has already deforested enough land to meet the future commodities demand and policies such and Brazilian NPIs can enhance such practices, preserving native forest and reducing LUC CO<sub>2</sub> emissions. Brazilian net-trade is projected to increase up to 2050 due to food/feed crop production

and keep increasing after that if the bioenergy market is established. However, this market increases land competition and Brazilian food prices, exemplifying a case of adverse side effect associated to the achievement of the 2 degree global warming target. Pasture relocation from other countries to Brazil in RCP2.6-SSP2 increases even more land competition and Brazilian food prices. On the other side, the no-mitigation scenarios do not depict high increasing food prices in Brazil; however, they are much more likely to overpass the 2°C warming threshold in 2100. The overall analyses indicate that each biophysical pathway has its own specific challenges associated, even when moving towards achieving the 2°C warming threshold. In the RCP6.0, depletion of Brazilian natural land is higher and promotes LUC CO<sub>2</sub> emissions and in RCP2.6 the increase in food prices can threaten food security. On the other side, the socioeconomic assumptions of SSP1 clearly depicts better socioeconomic and environmental outputs than the other SSPs. As presented in Figure 12, the SSP1 has the lowest food price in the RCP2.6. It suggests that decisions taken in the demand side are able to soften the adverse side effects that biophysical assumptions of RCP2.6 can imply to Brazil.

The analysis of the impacts of achieving the mitigation of deforestation targets for the next three decades contributes to policy design in Brazil and globally. If it were not the mitigation policy for Legal Amazon and Cerrado, the country would maintain its agricultural expansion over these areas as it did so far. By enforcing the policy, deforestation and LUC CO<sub>2</sub> emission decrease while the impacts on crop production are relatively low. The impact on pasture yields, however, are negative, and policies to soften it are required. Although the policy promotes the mitigation of deforestation and emissions in Brazil, the global emission reductions are lower than reductions achieved by Brazil. Leakage effects partially offset Brazilian mitigation in most of the scenarios and it highlights the importance of international cooperation towards effective global climate policy. Agricultural land relocation would go to non-forest areas if policies such as the Brazilian were encouraged in more countries. In this case, CO<sub>2</sub> emissions would be lower and promote a better overall result regarding global warming.

Considering national interests into the issue of reducing global emission, the challenge is to make the individual decision for limiting deforestation become an optimal decision and for as many countries as possible. In the case of Brazil, in RCP6.0, the policy prevents a net loss of 50 million ha of forestland to the detriment of a net decrease of 36 million ha of agricultural land (8 and 13 million ha, respectively, in RCP2.6). As in the social sciences, the overall evaluation is subjective. The policy considerably reduces

Brazilian deforestation and emissions but has some decreasing effect on agricultural production. By the environmental perspective, however, avoiding deforestation is good for Brazil independent of other countries decisions to reduce deforestation or not. At the international level, the research demonstrated that a global policy (Carbon emission prices) is more effective than national policies (NPIs) for preventing leakage and enhancing higher global CO<sub>2</sub> mitigation. Notwithstanding, the current political context is closer to national protective policies than to global emission policies. Brazilian policy reduces deforestation at the cost of only a minor decrease in production, which makes the policy environmentally worth. If other countries nationally protect their forests and Brasil do not, it is likely that Brazilian deforestation increases even more due to leakage effects. If this is the case, Brazilian NPIs are worth from the environmental perspective, because the policy preserves Brazilian forests from further deforestation. Therefore, policies for reducing deforestation in Brazil in this hypothetical circumstance is the optimal decision from the environmental perspective. However, for a global perspective, such policies are desirable to cover enough areas to avoid leakage effect, otherwise agricultural relocation will drive deforestation somewhere. In the case of Brazil, the country's deforestation mitigation policy is an optimal decision that contributes to build the global cooperation required to fully prevent leakage.

Besides this environmental analysis, the socioeconomic evaluation is important too. Of course, leakage effects from other countries to Brazil would be due to the relocation of agricultural production, which can enhance Brazil's economy. The crucial point here would be to design balanced policies to sufficiently protect Brazilian forests and, at the same time, encourage agricultural production over abandoned pasturelands. Though, even agricultural usage of abandoned pasturelands would compete with afforestation of these areas, which would be an important dynamic to stick to RCP2.6. Brazil has already enough agricultural land that enables the country to keep as an important player in the global agricultural market for the next decades. If the balanced policies are successful, Brazil can remain as an important player in the agricultural market, with no further deforestation, and regardless of the other countries choices for protecting their forests or not. Once this feasibility has been demonstrated here, the next step would be building the local knowledge to support the farmers' decision for going into abandoned pastureland instead of forestland.

There are only a few Brazilian land-use studies on the global perspective yet and this is in part due to methodological limitations. The usage of diverse models for addressing the same question, as done by Popp et al. (2017), is a good option to assess

the reliability of results. The development of MAgPIE-Brazil is a step towards such desirable context, where diverse methodological approaches can be used to answer similar issues. On one side, as results in section 3.1 demonstrated, the wide range of outcomes denote that there is still time to act and drive Brazilian land use accordingly. On the other side, as demonstrated by results in section 3.2, the relative global results are lower than the individual Brazilian achievement. Therefore, the time that Brazil may still have to act and drive its land use may also be used to design cooperative international policies in order to enhance global effectiveness. For doing so, other researches which specific focus on highly land-use dynamic countries are welcome, in order to identify and enhance their opportunities on making avoiding deforestation part of their optimal future land-use pathways.

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## APPENDIX 1

### Methodology for using MapBiomias (2019) data as validation in MAgPIE-Brazil

Land use data from 1985 to 2017 for Brazil is aggregated from Project MapBiomias - Collection 3.1 of Brazilian Land Cover & Use Map Series, accessed on 27/04/2019 through the link: <http://mapbiomas.org/pages/estatisticas>.

Data aggregation from MapBiomias to MAgPIE-Brazil follows the structure below:

MAgPIE variable = MapBiomias variable(s)

forestland = Floresta

managed forest = Floresta Plantada

cropland = Agricultura + ((Agricultura / Pastagem) \* Mosaico de Agricultura ou Pastagem)

pastureland = Pastagem + ((1-(Agricultura / Pastagem) \* Mosaico de Agricultura ou Pastagem)

other land = Formação Natural não Florestal + (Área não Vegetada - Infraestrutura Urbana) +  
Corpos D'água + Não Observado

urban = Infraestrutura Urbana

**IMPORTANT NOTE:** the variable "Mosaico de Agricultura ou Pastagem" from MapBiomias has been distributed over cropland and pastureland according to the share "Agricultura"/"Pastagem", as presented above.

MapBiomias			MAgPIE
Nível 1	Nível 2	Nível 3	Correspondent variable
1. Floresta	1.1. Floresta Natural	1.1.1. Formação Florestal 1.1.2. Formação Savânica 1.1.3. Mangue	forestland forestland forestland
	1.2. Floresta Plantada		forestland (managed forest)
2. Formação Natural não Florestal	2.1. Área Úmida Natural não Florestal		other land
	2.2. Formação Campestre (Campo)		other land
	2.4. Outra Formação não Florestal		other land
	2.3. Apicum		other land
3. Agropecuária	3.1. Pastagem		pastureland
	3.2. Agricultura	3.2.1. Cultura Anual e Perene	cropland
		3.2.2. Cultura Semi-Perene	cropland
3.3. Mosaico de Agricultura e Pastagem		proportional to cropland/pastureland	
4. Área não Vegetada	4.1. Praia e Duna		other land
	4.2. Infraestrutura Urbana		urban
	4.3. Outra Área não Vegetada		other land
	4.4. Mineração		other land
	4.5. Afloramento Rochoso		other land
5. Corpo D'água	5.1. Rio, Lago e Oceano		other land
	5.2. Aquicultura		other land
6. Não Observado			other land

Figure A1. Variable association between MapBiomias and MAgPIE.

Source: Adapted from MapBiomias (2019).

## APPENDIX 2

### Complementary figures

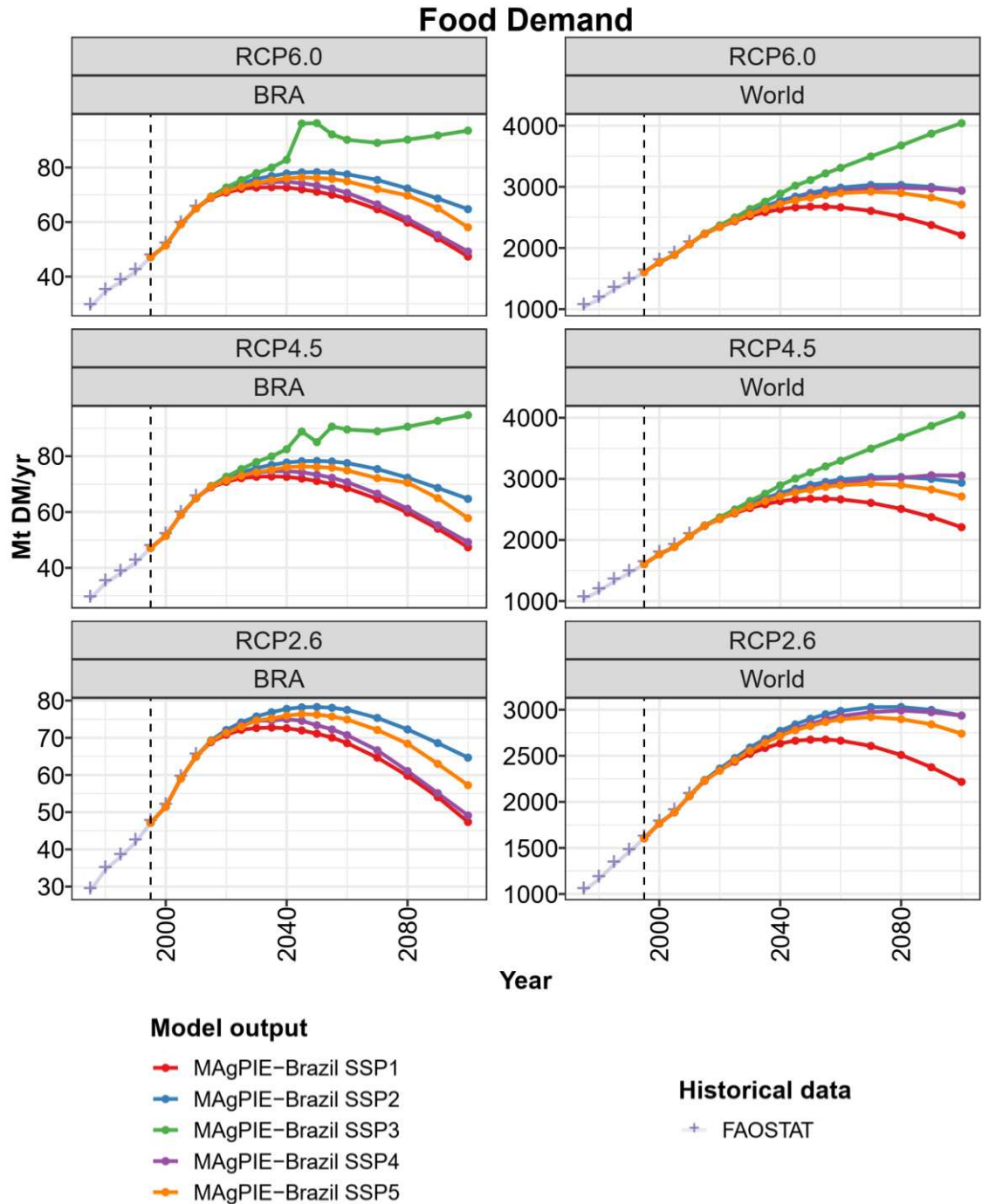


Figure A2. Food demand for Brazil and World. Figure shows that SSP2 and SSP3 have the high food demand in Brazil and globally. Figure also demonstrates that one SSP can present the lowest regional demand but the highest global demand. For example, in RCP2.6, SSP4 has one of the lowest trajectories in Brazil and has one of the highest in World. Eventhough in SSP4 the Brazilian demand is low, the high global demand in the same SSP can still drive Brazilian land use dynamics to increase production.

### Feed Demand

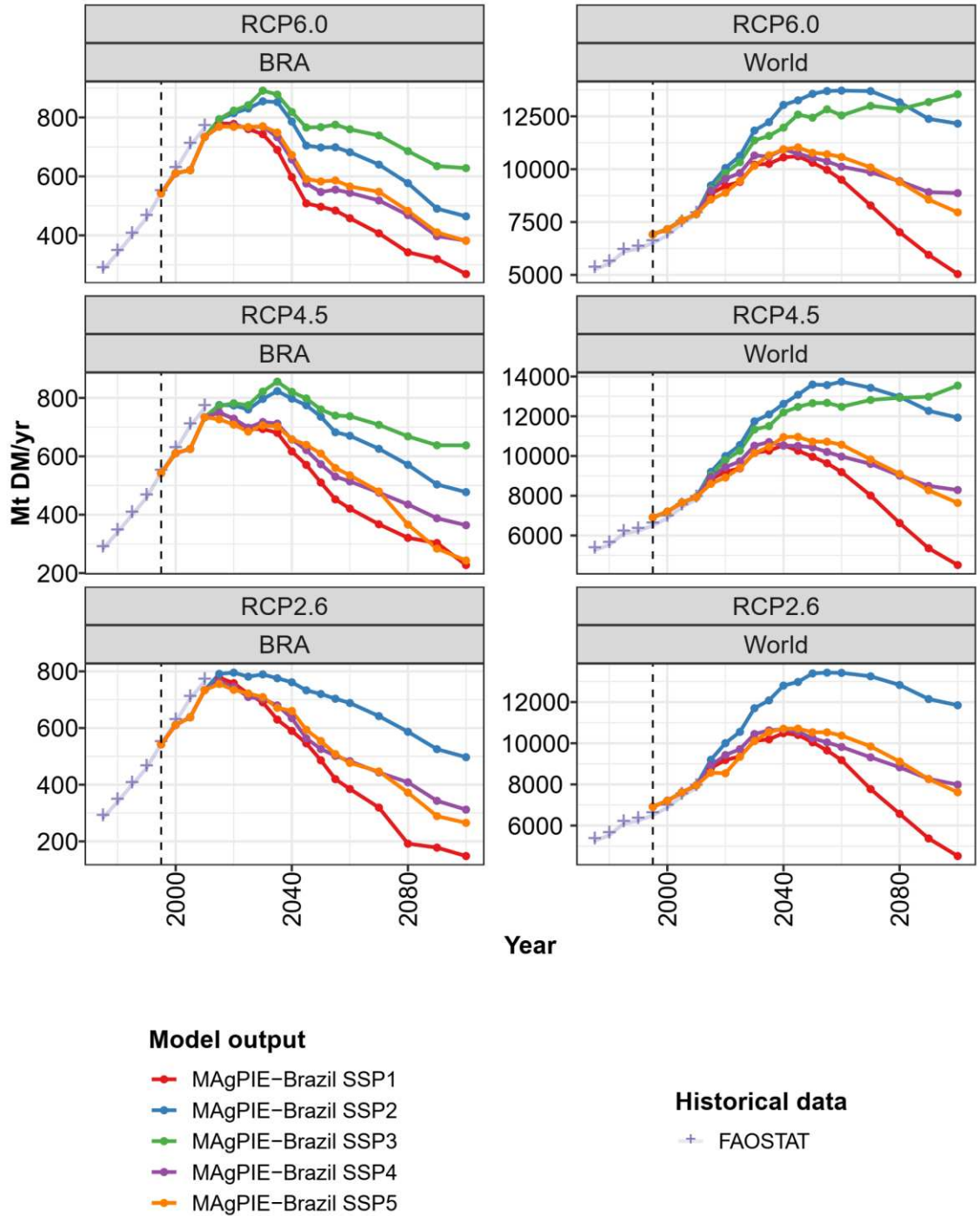


Figure A3. Feed demand for Brazil and World. Figure shows that SSP2 and SSP3 have the high feed demand in Brazil and globally.

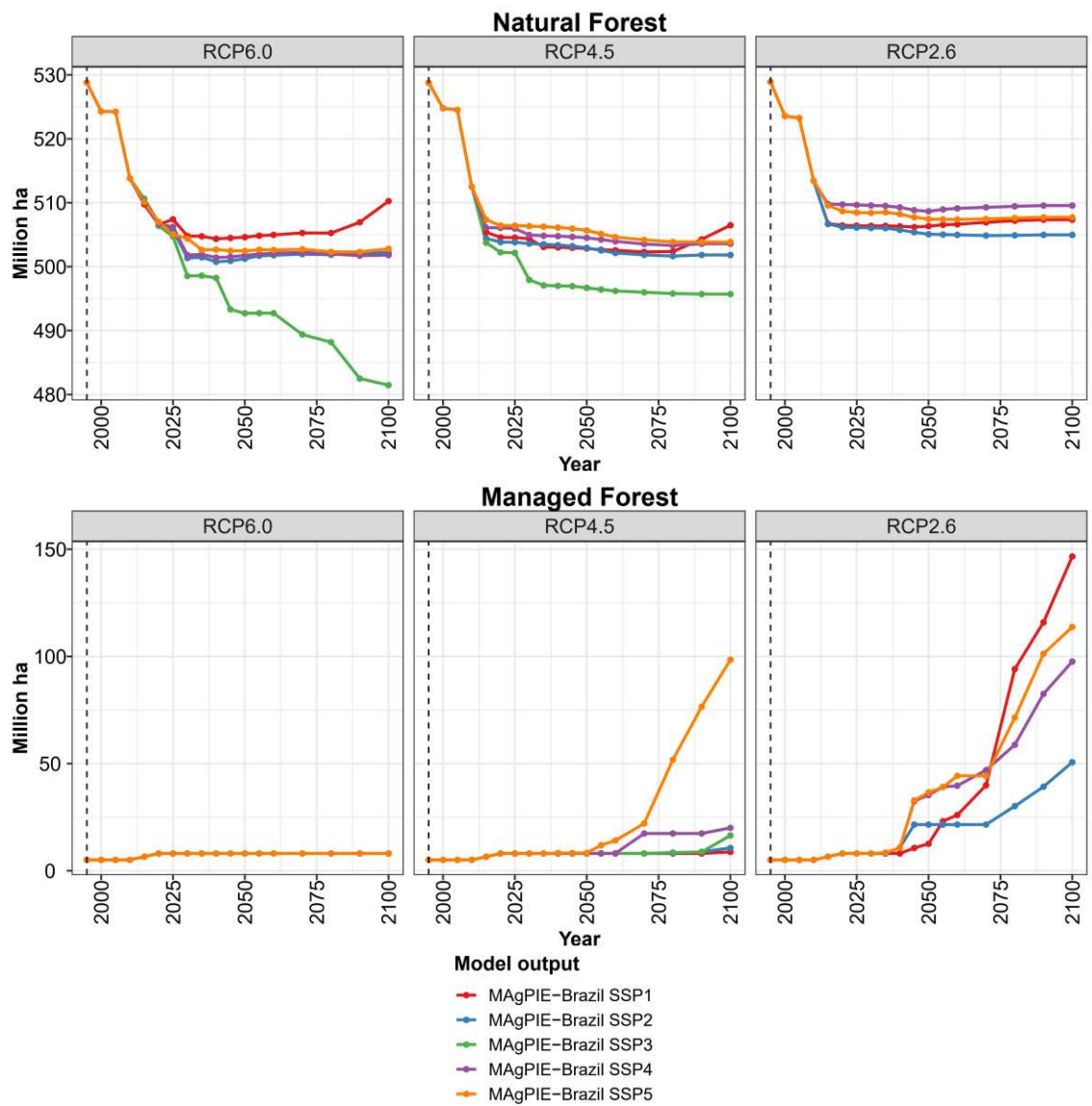


Figure A4. Brazilian Natural and Managed Forest. The Figures shows that increases in Forestland observed in Figure 5 are due to increases in Managed Forest.

Rainfed Pasture Yields from LPJmL in 1995

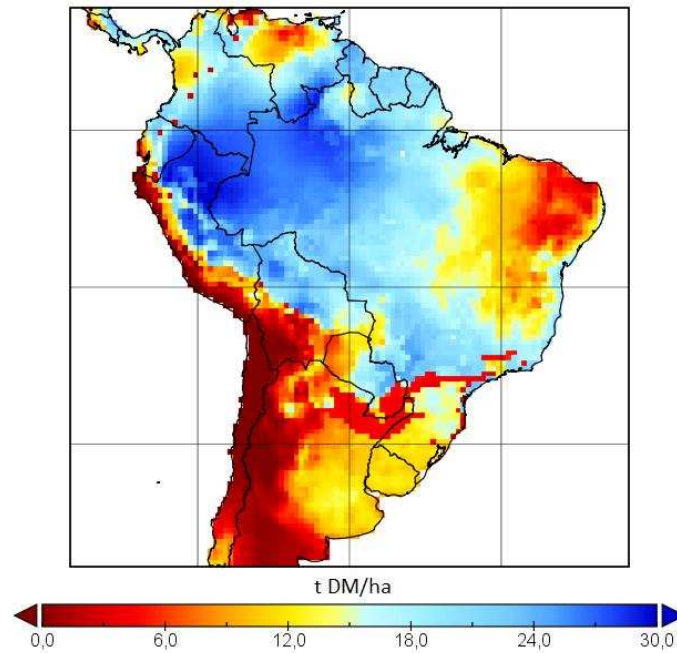


Figure A5. Rainfed potential pasture yields from LPJmL in 1995 used as input for MAgPIE. The yields are calculated by LPJmL using the Global Climate Model IPSL CM5A Low Resolution. The figure demonstrates an unusual low pasture yields in northern of the South region and in parts of Paraguay and Argentina.

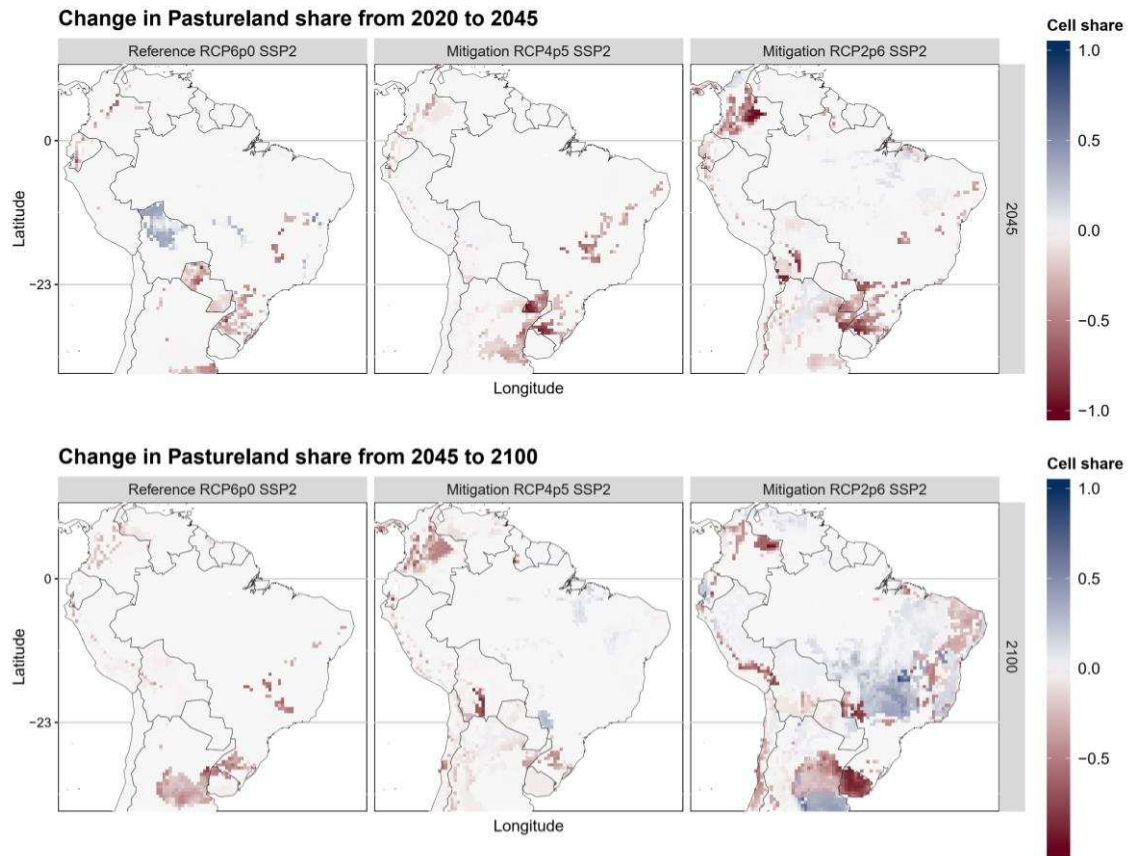


Figure A6. Change in Pastureland share from 2020 to 2045 and from 2045 to 2100. Figures demonstrate that there is practically no change in pastureland share in Center-West and parts of Southwest from 2020 to 2045, while it restarts to increase from 2045 to 2100.

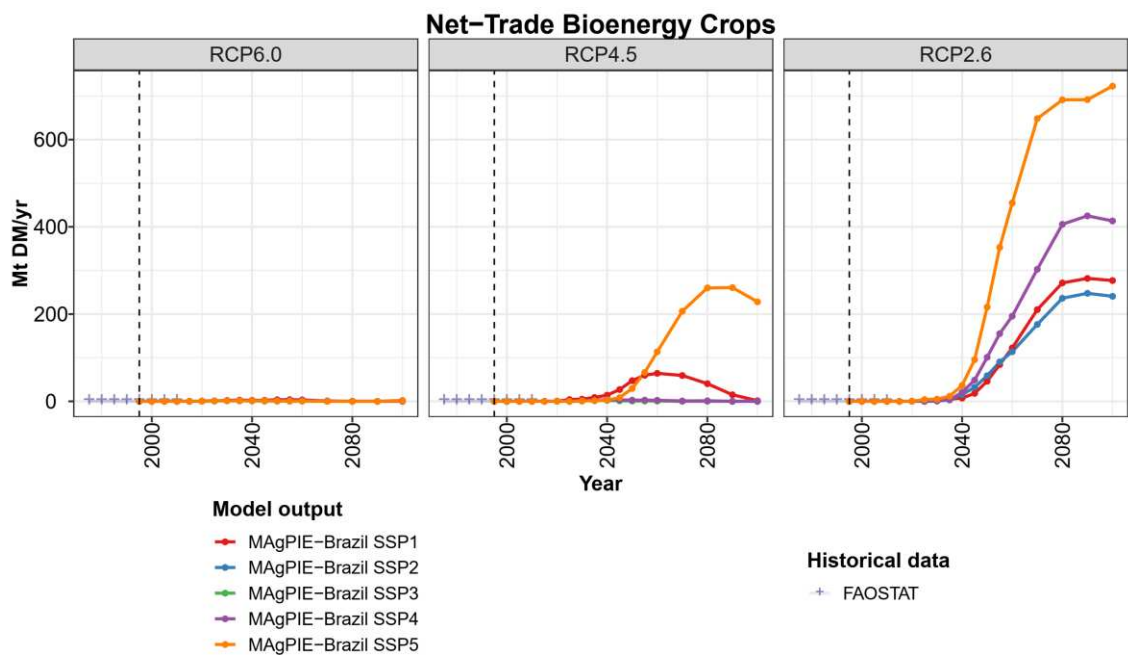


Figure A7. Brazilian bioenergy crops Net-Trade. Figures demonstrate how bioenergy crops net-trade increases as moving from RCP6.0 to RCP2.6.

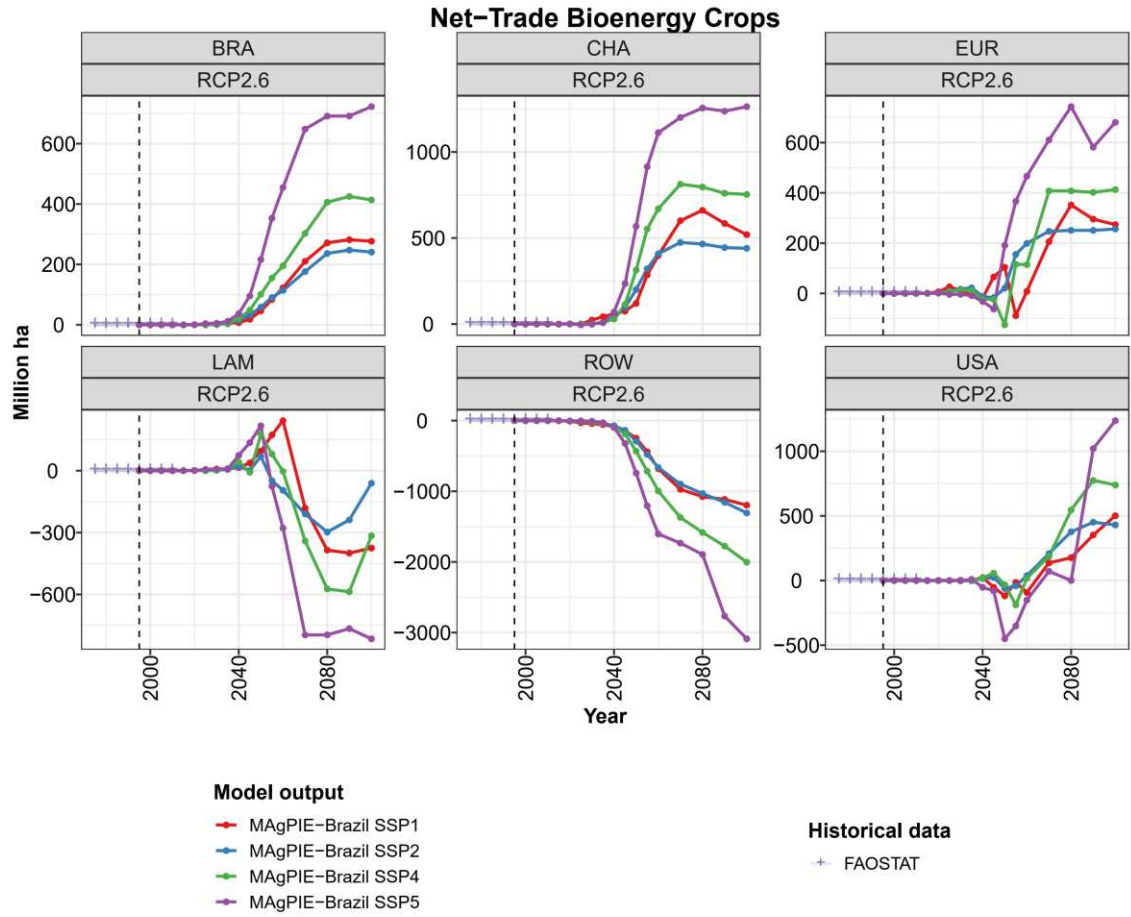


Figure A8. Net-Trade Bioenergy Crops for all MAgPIE-Brazil regions. The figures shows that Brazil, China, Europe and USA are bioenergy crops exporters in the RCP2.6.

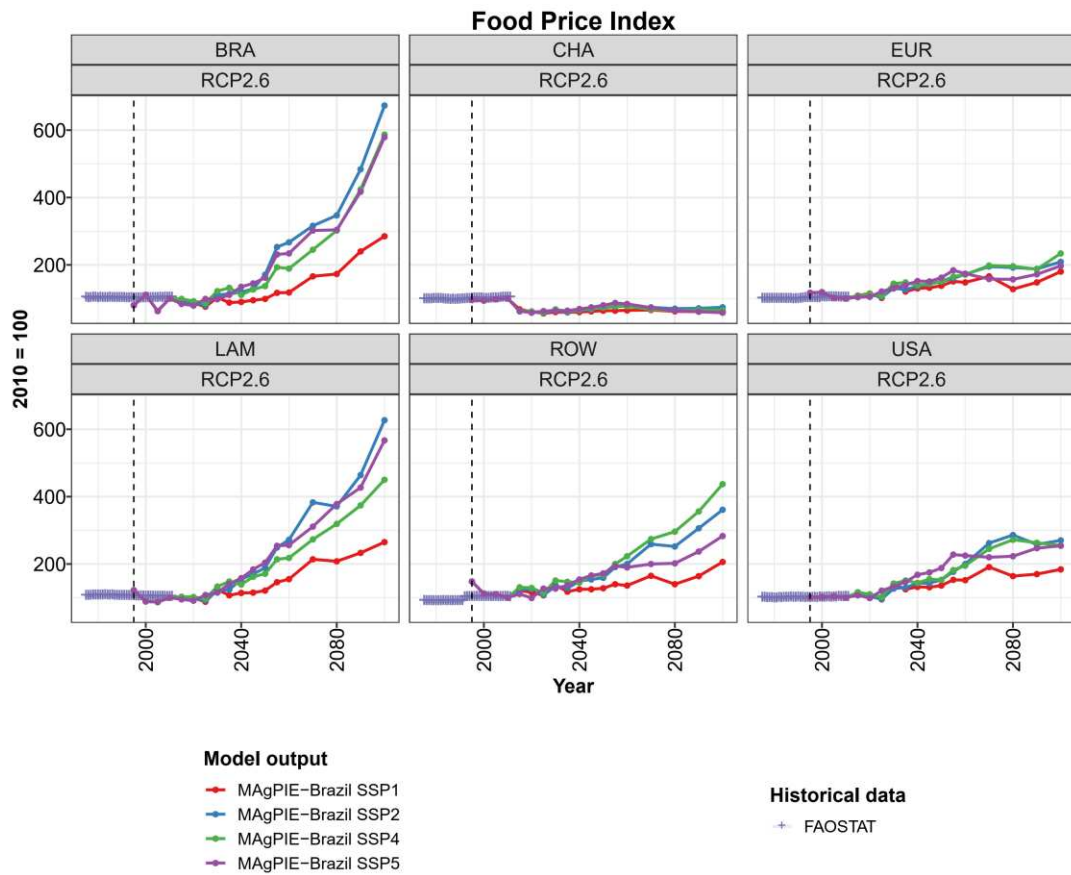


Figure A9. Food price index in RCP2.6 for all MAgPIE-Brazil regions. Figure show that food price index increases more in Brazil and Rest of LAM than in other regions.

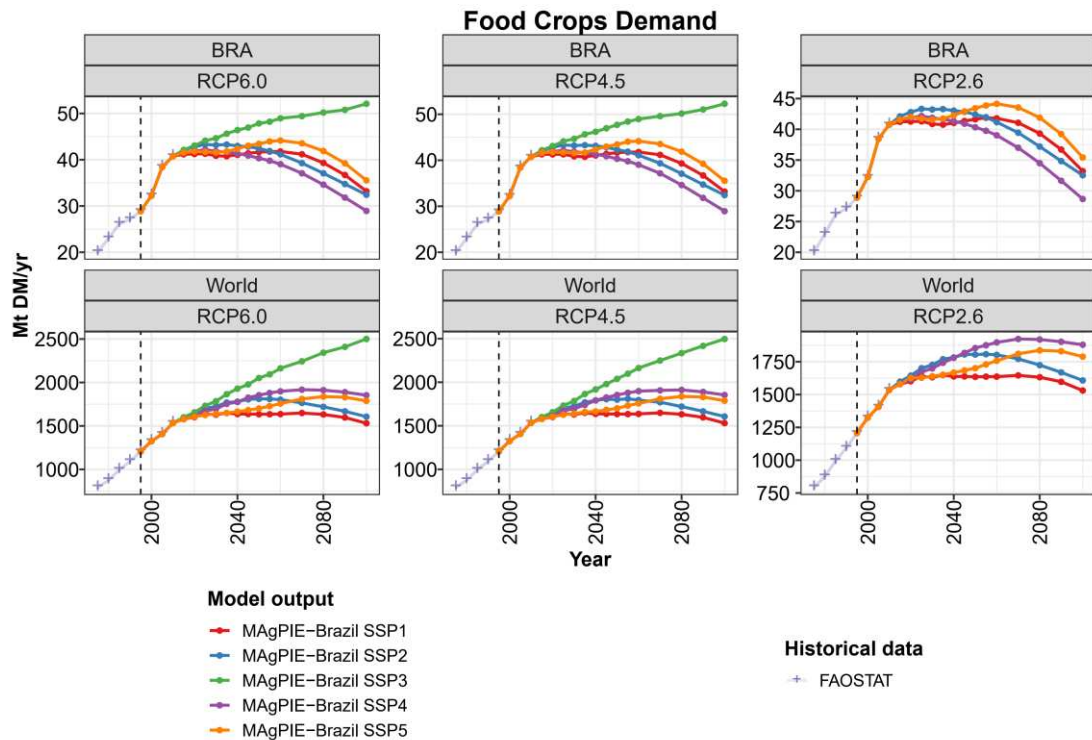


Figure A10. Food Crops Demand for Brazil and globally. The figure shows that food crops demand increases up to 2050 in Brazil and up to 2070 in the World in most of the SSPs.