Universidade Federal de Pernambuco
Centro de Ciências Sociais Aplicadas
Departamento de Economia

Pós Graduação em Economia - PIMES

Brazilian water resource impacts under global climate and biofuel demand changes

Ewerton Felipe de Melo Araujo

Tese de Doutorado

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Resumo

Cerca de metade da cana-de-açúcar produzida no Brasil é destinada à produção de etanol. Embora a agricultura de sequeiro ainda corresponda à maior parte da produção (79,44%), a irrigação vem crescendo em todas as regiões produtoras do país. O aumento da preocupação com as mudanças climáticas levou a mais iniciativas de formuladores de políticas internacionais para incentivar os combustíveis renováveis, que no futuro podem aumentar a demanda por etanol no Brasil. Este trabalho mensura os impactos na disponibilidade e nos valores econômicos da água diante de demandas maiores pelo etanol, e em diferentes cenários de comércio e clima, considerando as políticas de alocação de água atuais no país. Para atingir esse objetivo, é usada a plataforma de modelagem agro-econômica de uso da terra e água **MAgPIE 4** para desenvolver o modelo **MAgPIE-Brazil**. Todos os cenários estudados apontam uma expansão na cana irrigada em todas as regiões do Brasil tanto no médio quanto no longo prazo. O Semi-árido, região hoje pouco tradicional no setor, tem o maior crescimento do país em termos de uso de água e área irrigada de cana em todos os cenários. Analisando cenários sobre futuras fontes de biocombustíveis a serem adotadas, conclui-se que a simples substituição da cana-de-açúcar pela Cana-energia como fonte de etanol no Brasil não tem efeito positivo na redução do crescimento da escassez de água (medida aqui pelos preços da sombra da água) no Brasil, em especial no semi-árido. Esse efeito só é alcançado quando apenas biocombustíveis avançados são produzidos a longo prazo. Em relação às mudanças climáticas, os resultados mostram que, se políticas fortes de mitigação forem implementadas (como a restrição ao uso de combustíveis fósseis) e diante das políticas de alocação de água atuais, a escassez de água no Brasil poderá crescer significativamente, especialmente nas áreas mais vulneráveis em termos de disponibilidade hídrica. Sugere-se então, o uso de políticas públicas que reflitam os valores de escassez em cada região para desencorajar usos intensivos em água em regiões mais escassas, a menos que invistam em tecnologias que otimizem seu consumo. Ao mesmo tempo, os usos menos intensivos, como os associados ao abastecimento humano, seriam incentivados. Dessa forma é possível otimizar o uso da água, uma importante estratégia de gestão de demanda, que induz o uso eficiente da água, reduz as perdas e transfere os recursos escassos para setores que agregam um maior valor para a sociedade, contribuindo para o desenvolvimento social e econômico das regiões e do país.

Palavras-chave: Uso da água; Modelagem Global de Uso da Terra; Gestão da demanda Bioenergia; Mudança Climática

Abstract

About half of the sugar cane produced in Brazil is destined for ethanol production. Although rainfed agriculture still accounts for most of the production (79.44 %), irrigation has been growing in all producing regions of the country. Raising concern about climate change has led to more initiatives by international policy makers to encourage renewable fuels, which in the future may increase demand for ethanol in Brazil. This paper measures the impacts on water availability and economic values in the face of higher demand for ethanol, and in different trade and climate scenarios, considering current water allocation policies in the country. To achieve this goal I use the global, spatially explicit, economic land and water use framework **MAgPIE 4** to develop the **MAgPIE-Brazil** model. All scenarios studied indicate an expansion of irrigated sugar cane in all Brazilian regions in the medium and long term. The semi-arid region, which is currently not a conventional producing area in the sector, has the highest growth in the country in terms of water use and irrigated sugar cane area in all scenarios. Analyzing scenarios regarding future sources of biofuels to be adopted, I concluded that simply replacing sugar cane with Cane energy as a source of ethanol in Brazil has no positive effect on reducing water scarcity growth (measured here by water shadow prices) in Brazil, especially in the semi-arid region. This effect is only achieved when only advanced biofuels are produced in the long run. Regarding climate change, results show that if strong mitigation policies are implemented (such as restricting the use of fossil fuels) and in light of current water allocation policies, water scarcity in Brazil could grow significantly, especially in most vulnerable areas in terms of water availability. It is therefore suggested to use public policies that reflect the scarcity values in each region to discourage intensive water use in scarcer regions unless technologies that optimize their demand are developed. At the same time, the less intensive ones, such as those associated with the human supply, become more expedient. In this way it is possible to optimize water use, an important demand management strategy that makes water use more efficient, reducing losses and transferring scarce resources to sectors that add greater value to society, contributing to the socioeconomic development of the country.

Keywords: Water Use; Global Land Use Modelling; Demand management; Bioenergy; Climate Change

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CHAPTER 1

Introduction

Bioenergy production in large scale, as a strategy for climate change mitigation, has been viewed as a sustainable source of economic development. Because biomass production is rural-based and generally labor-intensive, expansion can lead to the creation of jobs and help to stem urban migration surging as a good opportunity in developing and specially underdeveloped regions [Moraes et al., 2011]. On the other hand, regions with poor economic indicators (such as low per capita income and human development level) are often subject to weak law-enforcement institutions and insufficient resources for pollution control and environmental management. This leads to concerns regarding the potential environmental problems involving biofuels. Among these problems, the possible impact on water resources is one of the main issues. [Guarenghi and Walter, 2016].

Bioenergy related water use can intensify existing water stress, increasing the importance of the proper management of water resources for reaching sustainable bioenergy production and use. Further research development is needed to support decisions on the design and assessment of policies and instruments that can minimize the negative impacts of bioenergy production on water availability and quality, considering both biomass production and the subsequent conversion to energy vectors (solid/liquid/gaseous fuels and electricity).

The largest quantity of water use for bioenergy production is associated with the cultivation phase of biomass (Feedstock production side – FPS) rather than the Energy Conversion side (ECS) [Moraes et al., 2011]. Impacts on water availability for FPS stem from two different, but interlinked, sources: Water withdrawals for irrigation purposes (impacting so-called "blue water"); and use of precipitation (impacting evapotranspiration (ET), or "green water"). Both types of water use have potential adverse impacts on downstream flows, depending on the type of feedstock, and previous land use.

Around 80% of Earth's evapotranspiration returns to the atmosphere through plant transpiration [Jasechko et al., 2013]; consequently, changes in vegetation cover, such as fast-growing woody bioenergy crops replacing pasture, annual crops, or native vegetation, can strongly impact water availability. A good example is the case of the Brazilian state of São Paulo, where the substitution of pastures and cropland for sugar cane cultivation has been causing water availability concerns [Boddey et al., 2008]. Although ET is usually lower in cropland compared to native grassland, or forest vegetation [Smeets et al., 2008], the longer growing period and the need for a larger amount of solar radiation for the sugar conversion process cause sugar cane to have a higher ET than most other crops, albeit still lower than grassland. [Wiedenfeld, 2004].

Evapotranspiration from crop cultivation has been shown to dominate water use of bioenergy production for most energy crops (rather than the industrial production process use)

[Watkins et al., 2015]. Gerbens-Leenes et al. (2012) predict, based on regional targets for biofuel production, that by the year 2030, the global biofuel blue Water Footprint could grow to 5.5% of the total available blue water due to bioenergy's increasing demand. In India and China, De Fraiture et al. (2008) found that, in order to meet national policy goals for biofuel production, cultivation of sugar cane and maize would have to increase 16% and 26 %, respectively. This represents an estimated increase in annual irrigation withdrawals of 35 km^3 and 30 km^3 in China and India, respectively, corresponding to 8% and 9%, of total irrigation withdrawals in 2005.

The goal of this research is to evaluate how bioenergy production efforts might cause side effects on water resources if the economic value of blue water is not considered, leading to scarcity in the more sensitive regions.

1.1 Brazilian Sugar Cane Industry

Brazil has the largest sugar cane area worldwide with 10.3 Million hectares (Mha) of harvested area in 2015, which corresponds to around 30% of the total global area [IBG, 2016]. Hernandes et al. (2013) evaluated both green and blue Water Footprints (WF) of biofuels in south-central Brazil (the country's leading sugar cane producing region), finding that, depending on the location, they range from 70-100 L/MJ for sugar cane ethanol and 40-50 L/MJ for biodiesel. According to Watkins et al. (2015), because Brazilian biofuel crops are mainly rainfed, an increase in the use of irrigation would lead to a reduction in total WF thanks to the increase in productivity. However, this also means an increase in blue WF of these biofuels. Due to the regional differences regarding soil, topography and etc, certain areas would perform better at converting irrigation water into yields and thus benefit more from it. The authors suggest that focusing growth in these regions could reduce biofuel crop expansion pressure in other regions; however, water availability for irrigation should be taken into account. The Cerrado region (where a significant part of this expansion happened) has soil characteristics that differ from traditional sugar cane areas, demanding irrigation to be used in order to increase yields [Scarpare et al., 2016]. Even the traditional areas, such as Northeast Brazil, a major part of which is in a semi-arid region, have witnessed increase in the use of irrigation, stressing even more its scarce water resources [Watkins et al., 2015].

The Northeast (NE)[1] region is the second largest sugar cane producing area in the country and accounts for about 10% of the total national production. Irrigation of sugar cane in NE Brazil is already an essential factor of the production, and recently irrigation has been demonstrated as a crucial element in increasing yields. In Piaui, a state in the Northeast region, there is a two-fold productivity increase in cane yield when more water is added to the plant. In the same state there is an example of a traditional mill (Coruripe) which has increased the irrigated area from 2,700 ha to 25,000 ha in the past 25 years [Moraes et al., 2016]. Moreover under climate change scenarios, Assad et al. (2008) have found that the cultivation of sugar cane, specially in non-traditional areas, such as semi-arid

[1] I use the Brazilian geopolitical division of 5 regions (figure 1.1), which are divided based on social, economic and geographical factors, and serve as a base to policy makers

areas, requiring for that intensive irrigation is expected to expand. Therefore, taking into account regional characteristics and the economic value of water in the expansion of biomass production is the main of Brazilian water policy challenges in the context of bioenergy.

Figure 1.1 Brazilian regional and state division

Sugar cane and ethanol productions have a deep negative effect on water quality in Brazil. The main cause of such impact is sedimentation downhill across the landscape from sugar cane fields that is deposited into wetlands, rivers, reservoirs and etc. The problem is further aggravated by the transport of contaminants such as pesticides and heavy metals commonly used for sugar cane cultivation in Brazil [Castillo et al., 2017].

Another important concern regards the use of vinasse for fertilization of Sugar Cane. Even though there are currently laws to control its use, surveillance difficulty reduces the effectiveness of the regulations. This proceeding leads to river polutions as the residuals may return to the water courses (besides also being difficult to detect and thus hard to control) [Moraes et al., 2011].

About half of the sugar cane produced in Brazil is used for producing ethanol. About three quarters of Brazilian sugar is exported, as compared to only 15-20% of the ethanol, with two thirds of this going to the major ethanol export market in the US. As the US market for ethanol is anticipated to grow in the future as a result of biofuel policies and blending mandates imposed by the Renewable Fuel Standard (RFS) and other state level iniciatives (such as California's Low Carbon Fuel Standard LCFS and Oregon's Clean Fuel Program), demand for Brazilian Ethanol is also expected to grow [Moraes et al., 2017].

In the coming years, global demand for agricultural products is expected to increase driven by a growing population and the need for renewable sources of energy. Brazilian Government project a substantial increase in agricultural outputs in the near future. The production of cereals, timber, sugar cane and other bioenergy products is expected to increase by at least 30% until 2026 [MAP, 2016].

Bioenergy demand is divided in two generations. The difference between them comes from the feedstock used in the process. In general terms, literature refers to the traditional first generation biofuels (1G) as those mainly based on sugars, grains, or seeds. They usually require a simpler and cheaper production process and so can be supplied at a lower price. In contrast, second generation biofuels (also called Advanced Biofuels, or 2G) are made from non-edible lignocellulosic biomass, including residues of crops or forestry production (corn cobs, rice husks, forest thinning, sawdust, etc), and whole plant biomass (e.g., energy crops such as switchgrass, poplar and other fast-growing trees and grasses). Biofuels obtained from vegetable oils produced from sources that do not directly compete with crops for high-quality land (e.g., jatropha and microalgae) can also be labeled as second generation biofuels. [Carriquiry et al., 2010]

Another source of second generation biofuel also under development (specially in Brazil and the USA) is Cane Energy. This new species of cane is designed to be more robust, with higher fiber content and productive potential than traditional sugar cane, becoming ideal for biofuel generation. The ethanol production process using this species is more complex and therefore more expensive (although it could be conducted all year)

The expected increase on demand for biofuel in the global markets, especially in the context of ongoing international climate change mitigation, may bring negative impacts on blue and grey water[2] availability in some Brazilian regions and change the economic value of water. Water scarcer regions, such as the Northeast, with greater potential for bioenergy expansion may aggravate its water resource problems. Water policies and instruments must be taken into account to prevent such an impact. Water conservation values should be considered in formulating energy expansion strategies.

[2]The amount of freshwater that is required to attenuate the load of pollutants based on existing water quality standards. [Castillo et al., 2017]

1.2 Literature Review: Brazilian water challenges in a biofuel demanding world

Given the relevance of the topic, current literature on water availability impacts of biofuel production comes not only from Brazil. Hao et al. (2017) shows how efforts to reduce Greenhouse gas (GHG) emissions through the incentive of biofuel might create or aggravate water scarcity in China, where production, based mainly on cassava and sweet sorghum, has grown recently and points the most favorable provinces for production from a water point of view. Similarly, Chartzoulakis and Bertaki (2015) revises the water scarcity problem in southern Europe.

In Brazil, Hernandes et al. (2013), Scarpare et al. (2015) and Scarpare et al. (2016), have shown the benefits of irrigation on sugar cane yield increasing and avoiding cropland expansion. However these analysis were all made in the South-Center region, where almost the entire production is rainfed. Hernandes et al. (2013) evaluates sugar cane waterfootprint for four states and concludes that, as their use of irrigation is limited, there is no evidence pointing to a critical pressure on water resources derived from sugar cane expansion in those areas. Scarpare et al. (2015) analyses irrigation's potencial to increase sugar cane prodution yields versus its water footprint in the Tietê-Jacaré subregion (state of São Paulo) and demonstrates that, in areas where water scarcity is not a pressing matter, yield gain from irrigation might be a way to release crop areas. Scarpare et al. (2016) has similar conclusions for the Paranaiba subregion.

Castillo et al. (2017) uses an environmentally extended multiregional input-output approach and, taking into account the spacial distribution of water among Brazilian regions, investigates the interregional virtual water flows derived from sugar cane cultivation for ethanol production. Results show that one third of total sugar cane water footprint is associated with bio- ethanol. Regarding interregional virtual scarce blue water flows, the most benefited states are the richer and non-water stressed southern and southestern states, where sugar cane production is rainfed. The northestern states, largely emcompassed by a semi-arid climate, are the top exporters of scarce virtual blue water. The state of Goias, in the Center-West, althouth not located in the semi-arid is also one of the main exporters due to its large use of irrigation.

Previous versions of the MAgPIE framework have been used for the analysis of complex land use change patterns. Biewald et al. (2015) addresses the production of cereals and oilseeds in Finland using the MAgPIE model. The advantage of a global model is the possibility of verifying the effect of changes in the international scene at the local level. Other versions of the same model produced concerning information on the potential climate change impact on agricultural production in the São Francisco river basin, the most important river in the Brazilian semi-arid region [Beck, 2013]; [Kölling, 2014].

As a previous version of MAgPIE was used, **MAgPIE 3** [Dietrich et al., 2019], the model was not regionalized (that is, Brazil was not a separate region, but part of Latin America) and so its validation was not quite good. Aware of this, Beck (2013) shows expansion of sugar cane crop area towards the semi arid in the presence of climate change and mitigation efforts that include increasing demand for biofuels. This result is a response to warmer temperatures (which sugar cane is well adapted to) and the use of irrigation from large water reservoirs, which allow production even with low rainfall indexes.

Kölling (2014) takes a similar strategy (although using a more recent version of MAgPIE 3) to study the same area. Sugar cane demand is again predicted to increase, mainly stimulated by latin American region demand. The cropland expansion is exclusively based on irrigation. Although having better validation, the model is not regionalized and the settings (the use of sugar cane as a source of biofuel is allowed only until 2050, and interregional trade of biofuels is forbbiden) do not allow a precise analysis to be made.

With regards to the main topic of this work, the use of a global model to estimate the economic values of water, Moraes et al. (2017) have calculated economic values of water for the main Public Irrigation Schemes in the sub-middle region of the São Francisco River Basin, in the Northeast, using MAgPIE. Landuse results from Beck (2013) and Kölling (2014) were used to estimate demand curves for agricultural producers using Positive Mathematical Programming. A comparison was made between the values found in the model and the prices established for agricultural use in the basin showing a distortion where prices actually charged were smaller. Given the increasing tendency of the water values found in that paper, this undervaluation of water might cause misallocations and unsustainable development in the future.

1.3 Objectives and motivation

The objective is to find the economic value of water for each of the five Brazilian regions under different scenarios in the bioenergy production context. To achieve this, I develop and adapt a global, spatially explicit, agro-economic land use model (MAgPIE) that can provide a holistic analysis of the effects of climate and socio-economic global changes in water resources focusing on Brazil and its regional differences. As secondary objectives, I explore the variations on sugar cane cropland and water use patterns under the scenarios considered (at regional and also state level). Thus providing input for policies that seek to combine economic welfare and environmental gains.

These economic values of water, which take future scenarios of global market and climate conditions into account should be helpful in supporting water policy design for Brazil, which may avoid conflicts and unsustainable development in the future, specially in water scarcer areas of the country. An example of a policy that can benefit from the results obtained here is the design of economic management instruments: both the collection, already allowed in Brazilian legislation, and the water markets, an option that is being studied.

It is important to also mention that the current study focusses on a quantitative assessment of water availability excluding issues related to water quality.

CHAPTER 2

Methodology

Integrated models combine the strengths of both economic and geographical models in order to make up for the inaccuracies of both types of models and try to assess the feedbacks between environmental factors and the global economy. MAgPIE and other Integrated land use models, such as GLOBIOM [Havlík et al., 2014], are a sub-category of the general category "integrated assessment models".

2.1 The MAgPIE 4 framework

MAgPIE is a global, spatially explicit, economic land use model with recursive-dynamic optimization, introduced by Lotze-Campen et al. (2008) as its **Version 1**. The model minimizes a goal function which groups different types of costs while fulfills demand for food, livestock and materials under both socio-economic and biophysical constraints [Dietrich et al., 2019], [Lotze-Campen et al., 2008], [Bonsch et al., 2015]. Costs considered in the goal function comprise, among others, the following categories:

- factor requirement costs - such as labour, machinery and fertilizers.
- land conversion costs - for afforestation, conversion from pasture to cropland and so on.
- investment and maintainance costs for irrigation infrastructure.
- investment costs for technological change.
- intraregional transportation costs - where the cost to transport the product to the closest market is accounted.
- trade costs - Commerce between different world regions.
- emission costs (when there is a carbon price, for instance)
- product processing costs, among others

The goal function is simply the sum of all costs at each time step. The optimization problem is solved through the allocation of nineteen[1] irrigated and rainfed cropping categories

[1] temperate cereals, tropical cereals, maize, rice, soybean, rapeseed, groundnut, sunflower, oilpalm, pulse, potato, cassava, sugar cane, sugar beet, fodder, cotton, pasture, bioenergy grasses and bioenergy trees

and six[2] livestock activities, land conversion and technological change. Each time step is optimized independently. [Lotze-Campen et al., 2010]. The model is implemented in GAMS language [GAMS, 2013] with data manipulation made with the use of R programming language [R Core Team, 2017].

The model takes land, water, yield information, costs and demand projections (based on exogenous population, income and diet projections) as inputs and endogenously appoints the optimal patterns for cropland, both irrigated and rainfed, forest, pasture and other vegetation.

In its **Version 1** the spatial resolution of the biophysical constraints was originaly three by three degrees cells, however in **MAgPIE 2** this was replaced by an aggregation system of 0.5x0.5 degree cells into clusters based on similarities. The cluster aggregation takes into account the biophysical similarities of the grid cells (such as climate, soil characteristics and water availability) and combines them into larger units. The number of clusters is determined at each model run and influences the results as the more clusters are used the less grid cells are combined in each cluster, making their data more representative. The clusterization process is important to keep computational feasibility [Dietrich et al., 2013].

The socio-economic constraints are aggregated at a global regional level. Until **Version 3** the world regions were predefined as shown in figure 2.1. **MAgPIE 4.0** presents a flexible region feature where this division varies according to the research focus. Flexibilization allows the world regions to be chosen country by country, isolating the area of interest of the research and those that have most commercial relations with it. Very small regions in terms of area and cropland generate poorly validated results. Due to its large size, Brazil is a good example of country that can be treated individually with this new feature, while keeping well validated results [Dietrich et al., 2019]. Figure 2.2 exemplifies the flexible demand regions.

MAgPIE 3 has introduced, and **MAgPIE 4** has developed and fully implemented, the concept of modularization, which makes possible to split the code into thematic components and to have different realizations of the same component. Different module realizations allow themes to be switched on and off depending on their impact on the researched topic (avoiding extra computational burden when not needed). [Dietrich et al., 2019]

Regional flexibility and the existence of module realizations make that there is not fixed a MAgPIE model, but many versions of it that might differ considerably depending on the chosen set up. For this reason it is necessary to adopt a new terminology approach: from model (MAgPIE before version 4) to framework (MAgPIE 4 and beyond).

2.1.1 Water use representation on MAgPIE

Water use in MAgPIE comprises the following categories: irrigation and livestock production, non-agricultural demand (comprising electricity production, domestic and industrial use) and environmental requirements. Both environmental requirements and non-agricultural use are exogenously given and are fulfilled first, limiting the water available for irrigation and livestock production. Industry, electricity and domestic demand are obtained from the global freshwater model WaterGap [Alcamo et al., 2003].

Rainfed crop production is based on green water (that is, precipitation infiltrated into the

[2] ruminants, swine, chicken, egg, fish and dairy products

Figure 2.1 MAgPIE Original 10 regions

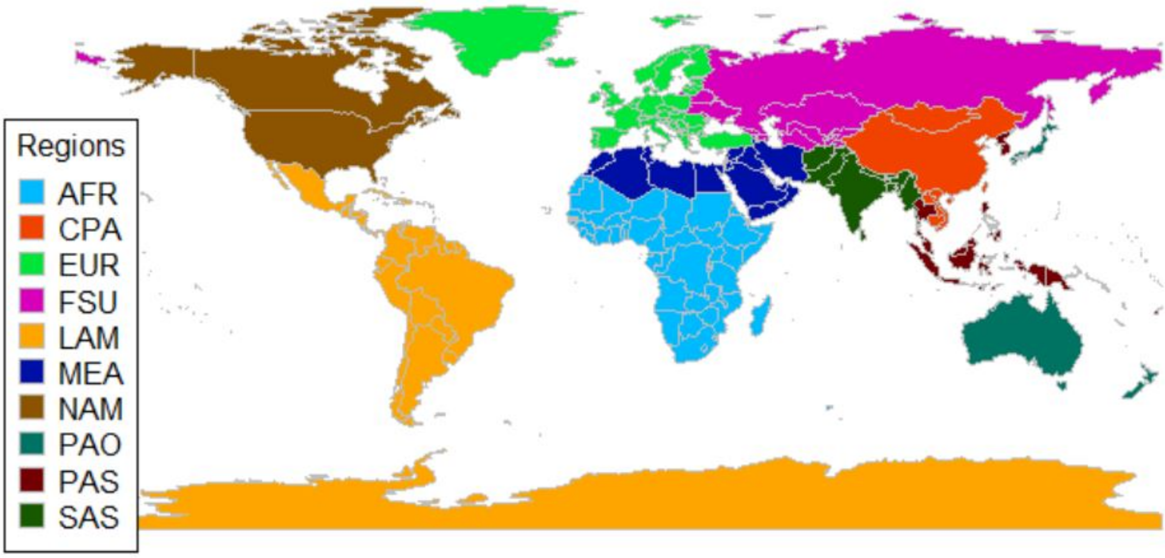
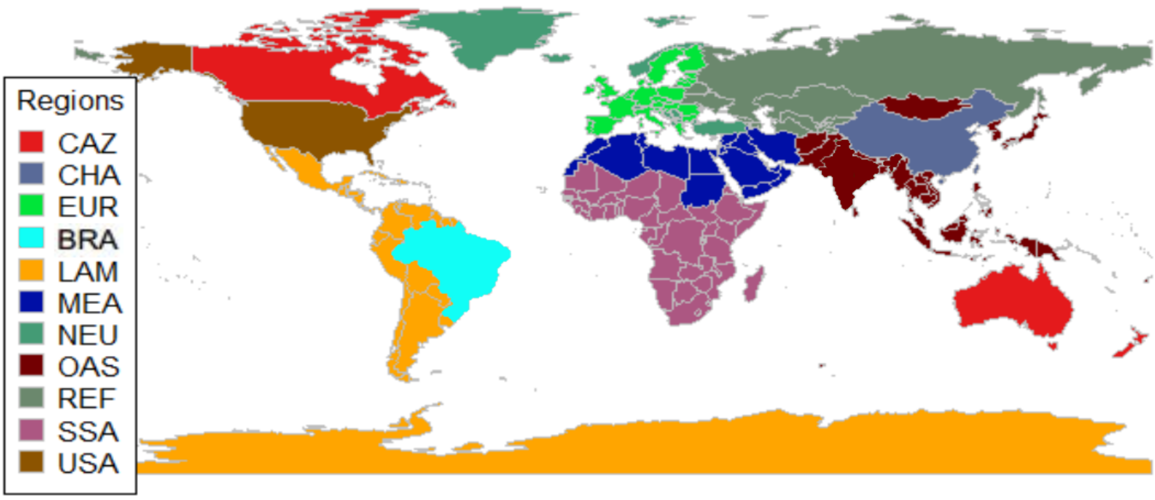


Figure 2.2 MAgPIE-4 Flexible World Regions



soil). The model endogenously decides wheter or not to use irrigation from blue water resourses (rivers, lakes, aquifers) to increase the yields [Bonsch et al., 2015]. Both green and blue water availability are provided to MAgPIE by the global vegetation and hydrology model LPJmL [Müller and Robertson, 2013] as are the crop yields for rainfed and irrigated areas. The amount of irrigation water per hectare that has to be applied to a field is simulated by LPJmL as the soil water deficit below optimal plant growth [Rost et al., 2008] and corrected for losses from source to field of 36% based on [Rohwer et al., 2007].

Another constraint for irrigated crop production is the existence of the required infrastructure in the area. Initial patterns for area equipped for irrigation (AEI) are exogenously taken from AQUASTAT database [Siebert et al., 2007]. MAgPIE endogenously decides, at each time step, to deploy additional infrastructure based on regional costs [Jones, 1995] for expanding the initial area.

The cost for increasing AEI initialy differs from world regions, with less developed regions having higher values then regions like the EU and USA. This means to represent factors like poorer infrastructure and difficulty in obtaining funding. As MAgPIE assumes that in the long term world regions tend to converge in terms of economic, institutional and technological standards, the investment cost required to equipp an area for irrigation linearly converges to the european level of 5700 US$ per ha by 2040.

2.1.2 Bioenergy representation on MAgPIE

Until its version 3, MAgPIE considered that 1G biofuel demand could be fulfilled by either ethanol (from sugar cane or maize) or biodiesel (from cotton, groundnut, oilpalm, soybean, rapeseed, sunflower or maize), although there was an assumption that this demand would vanish completely by the year 2050. The disappearance of 1G demand comes from an expected increase in 2G production capacity which causes a shift in the demand from 1G to 2G. 2G demand can be met by one of two groups of crops: bioenergy trees or bioenergy grasses.

Until the same model version, 2G demand was exogenously given by the REMIND model [Leimbach et al., 2009], while 1G demand follows [Lotze-Campen et al., 2014]. Both had their separate demands which were fulfilled independently, so the model could not choose the most efficient biofuels source (either 1G or 2G) for each region.

As was mentioned before, **MAgPIE 4.0** allows for the creation of parallel realizations for each topic being studied. For this research was created a new bioenergy realization more compatible with the Brazilian reality. Here I consider a single biofuel demand (sum of 1G and 2G demand from previously) that can be met by either 1G or 2G fuels throughout the whole period. The main advantage of this is the freedom to choose which is the most efficient source of bioenergy at each world region. As sugar cane is a feedstock with high productivity for ethanol, and has the potential to be an efficient biomass for second generation ethanol (through the Cane Energy species), Brazilian demand for this source does not vanish in 2050 as it did in the previous version. Other minor change was the inclusion of sugar beet as a possible source of ethanol.

While REMIND data takes into account the reaction of the demand according to the scenario chosen (regarding future socioeconomic and climatic conditions), [Lotze-Campen et al., 2014] considers biofuel policy mandates of the most important energy consumers and the level of international biofuel trade to create the demand. Thus, by adding these two sources, our total demand considers both socioeconomic and biophysical aspects of the bioenegy global market.

2.2 MAgPIE-Brazil

As this work intends to examine the impacts on availabilities as a result of a bioenergy growing demand in Brazil, a regionalization process was conducted to achieve a more detailed description of Brazil at the same time that the benefits of using a global model are preserved (such as trade). In the context of defining MAgPIE 4 as a framework instead of an inflexible model, I call this model **MAgPIE-Brazil**. The first step in the process was the use of MAgPIE 4‘s new feature of flexible regions. Brazil was separated from the rest of Latin America to which it was previously part by default.

The remaining regions were chosen based on their level of trade with Brazil, as well as their similarities among themselves. For instance, Latin America has some of Brasil's most important commercial partners while also have some less relevant ones, however due to the socioeconomic similarities the group was treated together as a global region. The USA and China as Brazil's most important trade partners and owning large areas are treated as single regions. Europe is also considered as a region and comprises both EU and Non-EU members (with the exceptions of Russia, Ukraine, Belarus, Moldavia and the caucasian countries). To enhance computational performance resolution needs to be reduced in the areas which are not as important for Brazil in terms of trade (specially of the products studied) so all other countries are grouped in a single "Rest of the World" (ROW) region. (Figure 2.3)

Simply moving Brazil from Latin America to its own region already brings benefits to the analysis, however, to really enhance the level of detail, a weighting process was included in the number of clusters per region. Originaly each world region would have a number of clusters proportional to its share of grid cells. With the weighting, it is possible to control which regions receive proportionally more or less clusters, and consequently more detail in the model. Table 2.1 shows the number of Brazilian clusters in different weighting set ups. All set ups have the same regions and number 1000 clusters. The greater the weight chosen for the region of interest the greater its proportion of clusters, however this relationship is not exactly linear.

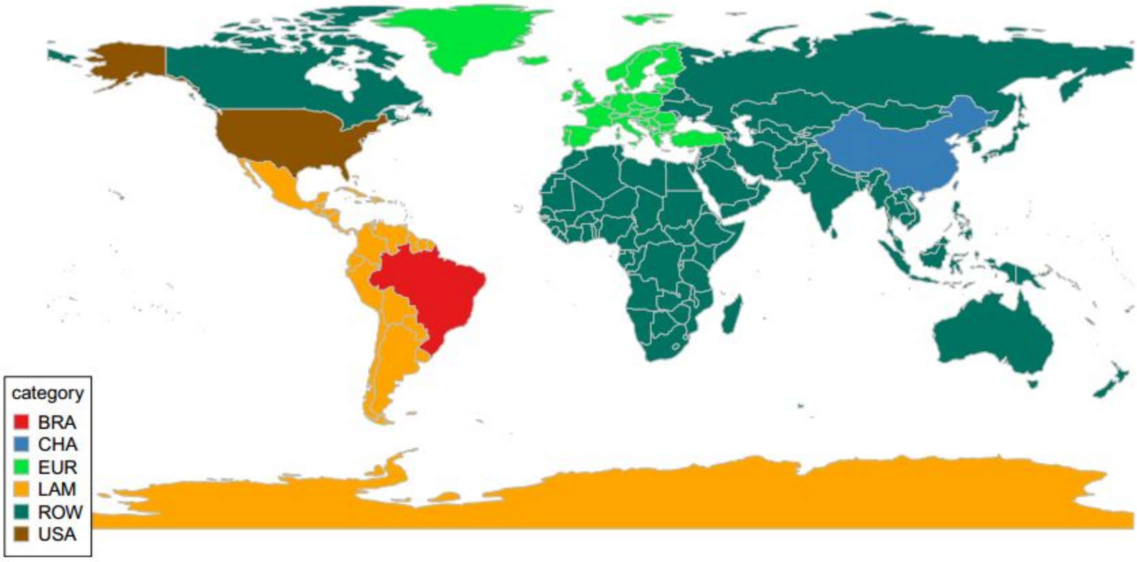
Table 2.1 Effects of weighting on cluster proportion

Model set up	Number of brazilian clusters
Non weighted	28
Brazilian Weight = 2	110
Brazilian Weight = 5	258
Brazilian Weight = 10	736

Source: Own elaboration

As Brazil has a total of 4.08% of the total grid cells, The gains in terms of analitical detailing

Figure 2.3 MAgPIE-Brazil



of the region are notorious. I use in this study a weight of 5 for MAgPIE-Brazil as it gives a better distribution both providing high detail in Brazil and relative importance to its commercial partners. As discussed, to reduce resolution, the ROW region has its weight set to 0.5.

As the cluster division of the territory follows only natural characteristics, it is important to aggregate the area into local subregions that have economic and socio-political meaning. This analitical level is chosen according to the research focus. This work uses the 5 Brazilian regions as they are both biophysically and socio-economically distinct and also are used as base to formulate national policies. The region's size is also an important factor. Examining too small areas could lead to bad validation as MAgPIE-Brazil could consider optimal to allocate some crop (or other land type) to neighboring areas with similar characteristics. As some Brazilian states are biophysically close, using state level would be problematic as the model has no additional indicators to decide where to allocate each crop, leading to differences to the observed patterns.

2.2.1 Differences between MAgPIE-Default and MAgPIE-Brazil

Due to the weightening process, each of the Brazilian clusters is composed by a smaller number of grid cells than in the default version. As biophysical data (at cluster level) is built by the aggregation of all the individual data from the 0.5x0.5 degree grid cells that form a cluster, the smaller number of grid cells implies that the cell´s characteristics are less diluted in the aggregation and the cluster level data gives a better representation of the region.

Examples of this better specification are many, from transport costs to production yields and water availability. Transport costs are measured as proportional to the distance from the grid cell to the closest market (nearest city with at least 50.000 inhabitants) and then aggregated as an average to the cluster. Too big clusters may include both high and low transport cost cells. After all grid cells are averaged, this would lead to an undervaluation of transport costs for more isolated areas and an overvaluation of less isolated areas.

Similar problems tend to appear on productivity related data, such as crop yields and water availability. Clusters with an excessive amount of grid cells, despite being created based on similarities, generate overestimations and underestimations that might alter the model‘s optimal solution.

Table 2.2 Changes to transport costs and water availability after regionalization

	MAgPIE-default	MAgPIE-Brazil
Total Transport Cost (US$ per Year)	14172	7971,4
Transport Cost of Cluster with Highest value (US$ per Year)	10392,947	664,22
Area weighted average Transport Cost (US$ per Year)	83,94	51,1
Transport cost standard deviation	27,04	8,3
Total Water Availability (MHa)	3639	3639
Water Availability of Cluster with Highest value (MHa)	2854	528
Area weighted average Water Availability (MHa)	31,87	24,76
Water Availability standard deviation	9,64	7,45

Source: Own elaboration

Table 2.2 shows transport costs and water availability change with the different model versions. With less and larger clusters MAgPIE-default has higher average values for both variables (average transport cost decreases from 83,94 to 51,1 US$ per Year and average water availability falls from 31,87 to 24,76 MHa). Those values are equally used for all cells which compose the cluster compromising the perception of the model regarding the particularities of each region as the cells compounding the clusters are homogenized. For instance, clusters with higher transport costs are less likely to be chosen by the model to became cropland, so a large cluster whose cost was increased by the presence of isolated grid cells is likely to be disregarded as a productive area, even if some parts of it are close to big cities (small transport costs).

The smaller standard deviations for both variables also indicate that MAgPIE-Brazil reduces the discrepancies between clusters caused by the aggregation of too many cells, avoiding sudden variations in the allocation of cultures from one time step to the other.

Figures 2.4 and 2.5 show the behaviour of clusters under MAgPIE-default and MAgPIE-Brazil (each color represents a different cluster). It is visible in MAgPIE-Brazil the higher level of detail on the subdivision of Brazil and the countries considered to be Brazil’s main trading partners which are placed as individual regions in this version of the model. The rest of the world, less important for this work, is treated much more homogeneously.

After the model run, the results at cluster level are desaggregated back to grid cell level and than aggregated to Brazillian region level. With clusters that represent better the biophysical particularities of the area, the results obtained at geopolitical level are much more accurate.

Figure 2.4 MAgPIE-Brazil: Cluster division

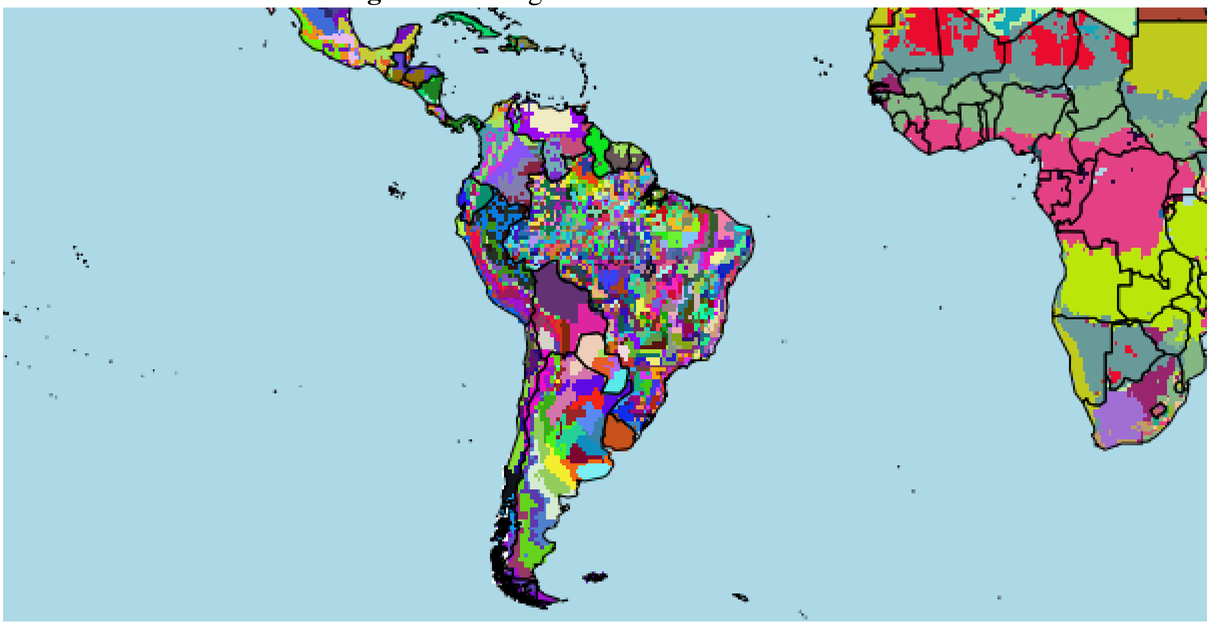
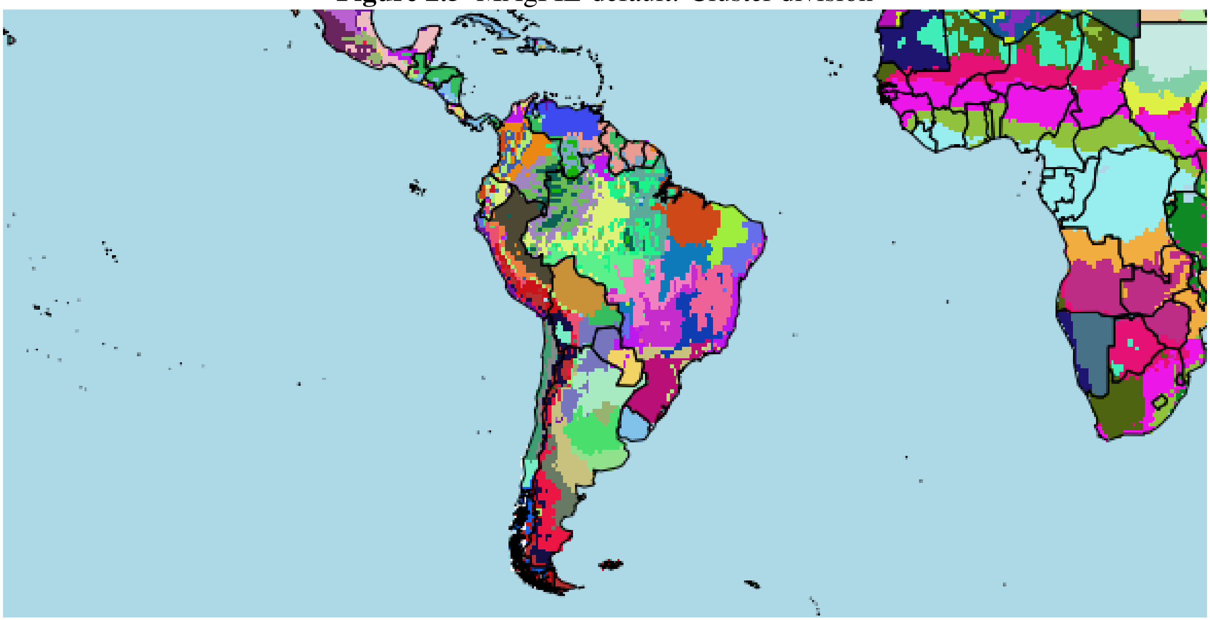


Figure 2.5 MAgPIE-default: Cluster division



Not only cluster level data suffers changes with the regionalization process. As in MAgPIE-Brazil the country is a world region separated from Latin America, changes to socio-economic data are also observed. Instead of composing Latin american data Brazil is in its own region, which avoids overestimating or underestimating variables that differ between Latin America and Brazil (the effect is similar to the effects of smaller clusters discussed before). Table 2.3 compares input data from the Latin America region of MAgPIE-default and the Brazil region of MAgPIE-Brazil.

Table 2.3 Brazilian socioeconomic data as a single region in MAgPIE-Brazil and as part of Latin America in MAgPIE-default

Variable	MAgPIE-Brazil	MAgPIE-default
Share of vegetables and fruits in the diet (%)	0.055	0.059
Per capita income (US$/year)	5629.875	5005.435
Share of people living in poverty (%)	0.124	0.100
Food expenditure per capita (US$/year)	609.845	627.054
Landuse intensity indicator	1.140	0.990

Source: Own elaboration

Other model dynamic significantly altered by the regionalization is intraregional trade. Because MAgPIE only considers interregional trade, internal movements of goods can not be observed. Hence, considering Brazil as part of Latin America omitted all international trade between Brazil and the Latin american countries for considering it internal trade. Another problem is that, as the model does not differentiate which part of the region produces each crop (as long as the total regional demand is observed), another Latin american country was able to fulfill a great part (or even all) of the Brazilian demand for some product even in a scenario where international trade was restricted.

Figure 2.6 was obtained as a result of a MAgPIE-default run and shows how almost no production of tropical cereals was allocated to Brazil, even though it is a major contributor to its demand. The light blue areas represent the cropland for tropical cereals. It is possible to observe that, even with the hypothesis of no trade, most production inside Latin America was destined to a small region between Uruguay and Argentina and to the northwest of South America.

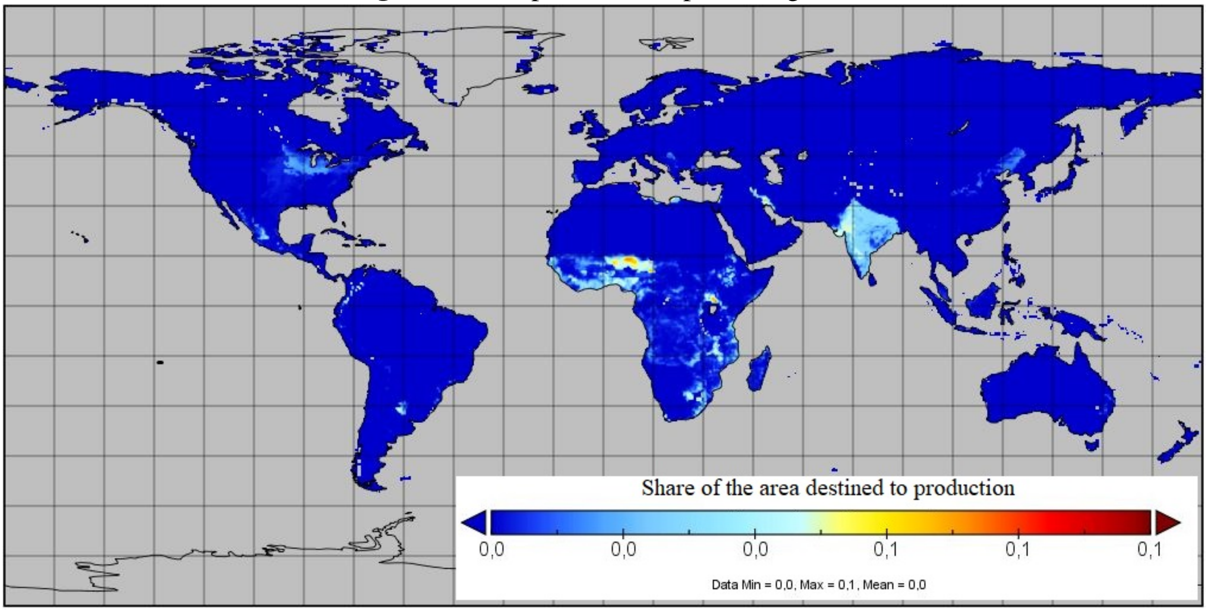
Regionalization allows this commercial relations to be observed, as well as avoids cases where an internal demand is fulfilled by production taking place outside the country.

2.3 Data

MAgPIE-Brazil uses a great number of different data bases. Here is shown which kind of information is obtained from some of the most important sources.

- FAO - emission values, crop production, livestock production, values of production, food supply, forest extent, food price index, energy requirements [FAO, 1997].

Figure 2.6 Tropical cereals producing area



- GTAP - Trade related data, transport costs [Narayanan and Walmsley, 2008].
- World Bank - GDP, Population, state of development, irrigation related costs [Worldbank, 2013].
- REMIND - Bioenergy demand and production [Leimbach et al., 2009].
- [Dietrich et al., 2014] - technology related parameters

As was already mentioned, the LPJmL model [Müller and Robertson, 2013] is responsible for the great majority of biophysical data, including those related to water, such as:

- Blue and Green water availability
- water demand for irrigation
- water demand for livestock
- production yields (both irrigated and rainfed)
- production yield variations due to climate change
- increase in water demand for irrigation due to climate change

I, in particular, used water consumption and irrigated area information for Brazil from two Brazilian data bases [fun, 2011] and [atl, 2017] with the purpose of validating the model results. The procedure to obtain the best comparison base is explained in the next chapter.

CHAPTER 3

Model Validation

The goal of validation is to understand how precise are the projections made by MAgPIE-Brazil when compared to observed data. If the model projections for the first time steps are good when compared to the observed data it is reasonable to assume the future projections will be reliable. This process consists of comparing a initial time step result of MAgPIE-Brazil with observed data from a reliable data source for the same year to see how they fit.

It should be highlighted that MAgPIE-Brazil is not expected to be perfectly precise on its projections. The model simply chooses the optimal allocation based on the input data and future scenarios selected. Besides the wide range of data non observed and not considered by the model, there is also the fact that real life often does not follow "optimal patterns", be it due to wrong incentives, lack of technology or any other reason not modeled by MAgPIE-Brazil.

Sugar cane irrigated crop area validation used [atl, 2017] values for 2015 and compared it to the models projections for the same year. The water use observed data was built with the use of sugarcane irrigated land use data from [atl, 2017] for the year 2015.

Related to water use data, as the data source atl (2017) only considers water requested by the producers as water rights, not the water effectively used in the irrigation, considering it to validate water use would disconsider the effluent from biofuel production (water that comes from the Sugar Cane after it is grounded) used in the irrigation. As MAgPIE-Brazil results are in terms of plant needs, a good validation demands a data base that represents what is actually given to the crops.

With that in mind I constructed the 2015 ANA/FUNARBE water usage data base by applying [fun, 2011] water consumption coeficients to the crop area given by [atl, 2017]. This created a more reliable value for water use which was then compared to the model results.

3.1 Sugar cane irrigated crop area

Starting with figure 3.1 which shows the comparison of the ANA/FUNARBE data (in the horizontal axe) and MAgPIE-Brazil projection (vertical axe) for each of the five Brazilian regions regarding total and sugar cane irrigated areas respectively. Each point represents one of the regions. The 45° diagonal line shows the points where the values for predicted and real data coincide. The closer from this line the region points are, the better is the projection for 2015.

So that validation doesn't have to rely only on how the points look, I use Willmott's test of model performance [Willmott et al., 2012]. This measure is bounded by -1 and 1 and is related to the accuracy of the model (negative values point to negative correlation). Willmott index close to one, as is our case, reflects almost perfect fit between model and [atl, 2017] values.

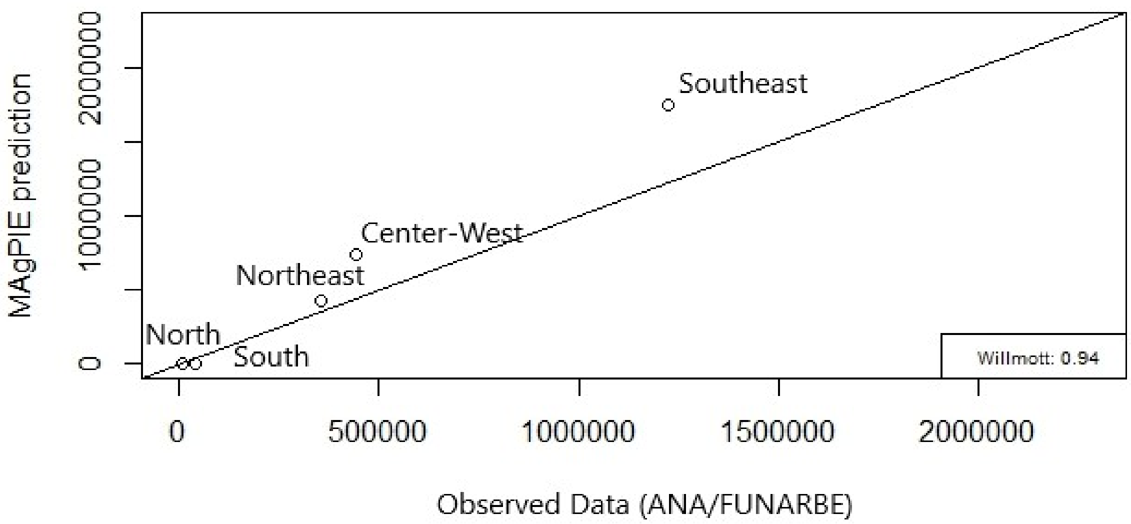
The actual numbers are shown in table 3.1. It is visible that the projection is quite good. The regions of North and South present the weaker projections, however as these are the least important areas for this crop, and their production in reality is very smaller than the other three, the analysis is not harmed.

Table 3.1 Sugar Cane irrigated area validation - 2015

Region	ANA/FUNARBE data (Ha)	MAgPIE-Brazil (Ha)
Northeast (NE)	355.579,58	420.303,39
North (NO)	8.089,31	1.282,89
Center-West (CO)	441.251,03	699.856,61
Southeast (SE)	1.223.442,19	1.660.181,16
South (SU)	40.250,89	0,00

Source: Own elaboration

Figure 3.1 Performance plot: sugar cane irrigated area (HA) - 2015

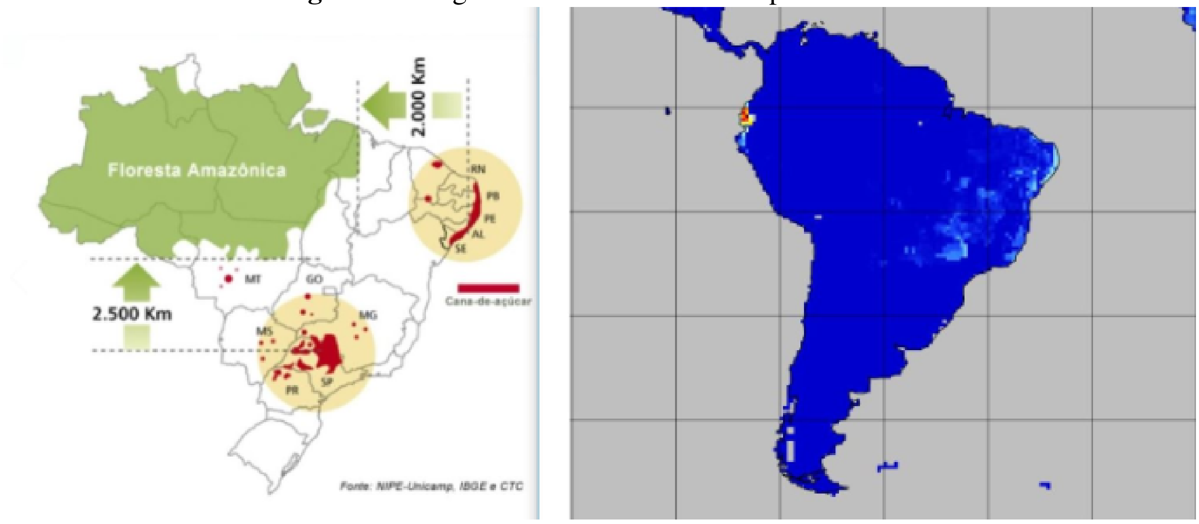


If each state's results are observed, because Brazilian states are geographically very similar (same soil, climate and socioeconomic features), MAgPIE-Brazil ends up swapping crop areas from where they actually are to neighboring states. An example happens between the states of Alagoas and Bahia. While in reality the former one responds to 411.298 Ha of irrigated crop area and the later to only 171.036 Ha, MAgPIE-Brazil predicts that in 2015 Bahia will have 356.546 Ha and Alagoas only 38.474 Ha of that land type.

This is the main reason our results will be focused at regional level, although general validation at state level is not entirely bad as Willmott test at 79% shows that, in general terms, results at this level are also satisfactory.

The good projection of the model can also be attested by figure 3.2 comparing the map of sugar cane production from the Brazilian sugarcane industry union (UNICA) (on the left, where the red areas represent sugar cane cultivation in 2013) with MAgPIE-Brazil crop area map in the 2015 time step (on the right, where the lighter blue show the higher concentration of sugar cane crops). Important to note that both productive areas viewed in the map on the left are well predicted by MAgPIE-Brazil, being both the lighter areas appearing on the right.

Figure 3.2 Sugar cane cultivated area map validation



3.2 Blue water use for sugarcane irrigation

The main producing sugar cane areas show reliable results regarding water use. Willmott's test of 96%in figure 3.3 indicates a great level of fit. Table 3.2 indicates how close the values are considering no constraints were imposed to the model to obtain such similar results.

The South-Center axe, composed mainly by SE and CO regions, being responsible for the largest irrigated areas but at the same time using proportionally less water then the NE, as can be seen in table 3.2 is another important result in terms of validation. As was mentioned, this is due to rainfall level, relief, soil and climatic characteristics of these regions, that encourage the use of rainfed production.

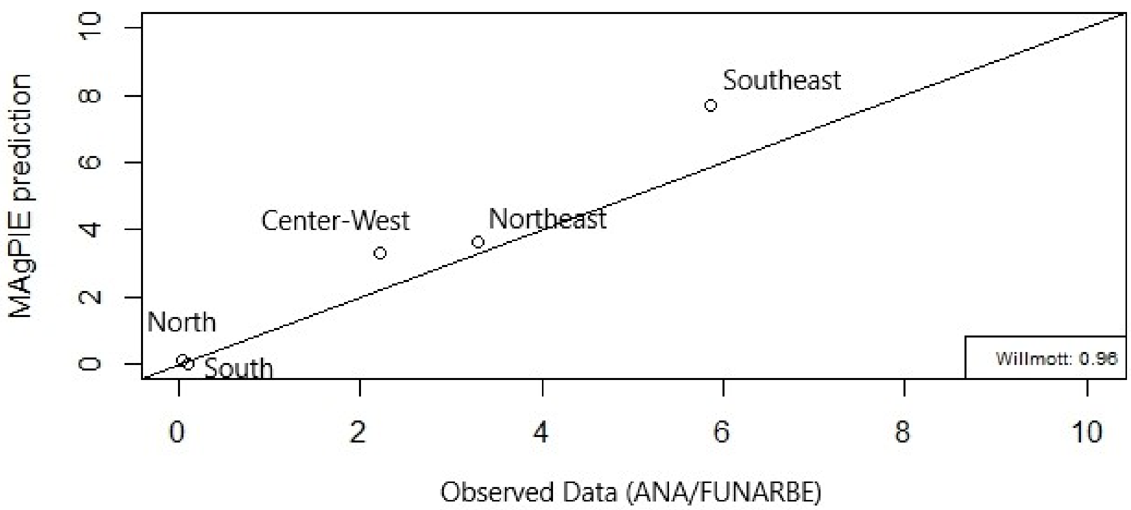
A joint look at water use and regional shares of irrigated crop area as shown in figures 3.5 and 3.4 points this relation more clearly. Although responsible for only 17% of the irrigated area, the NE region uses more then 28% of the country's irrigation water. This behaviour is reflected very well by MAgPIE-Brazil which captures the larger share of the NE in water use than in crop area.

Table 3.2 Sugar cane blue water use validation - 2015

Region	ANA/FUNARBE data (Km³/ano)	MAgPIE-Brazil
Northeast (NE)	3,30	3,59
North (NO)	0,05	0,12
Center-West (CO)	2,22	3,22
Southeast (SE)	5,85	7,29
South (SU)	0,10	0,00

Source: Own elaboration with data from ANA and FUNARBE

Figure 3.3 Performance Plot: Sugar cane blue water use (KM³/year) - 2015



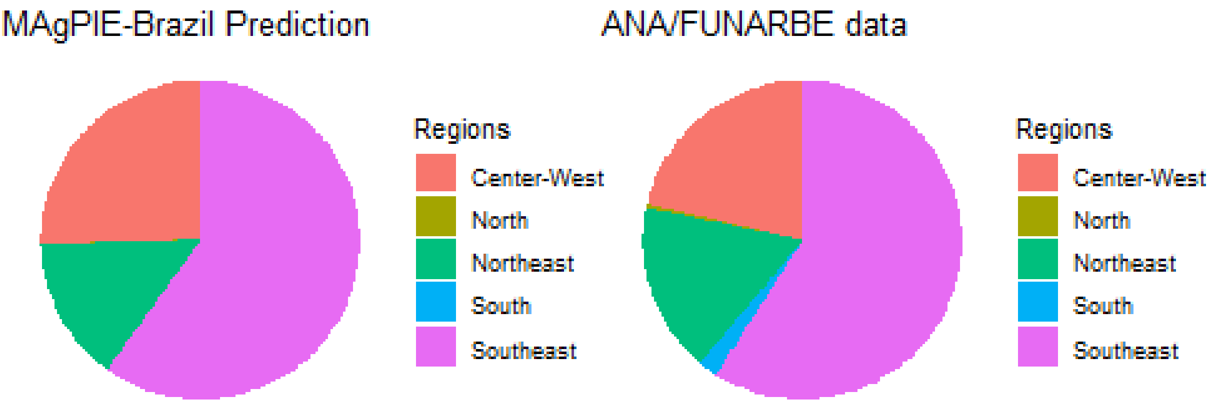


Figure 3.4 Regional share of sugar cane irrigated crop area validation - 2015

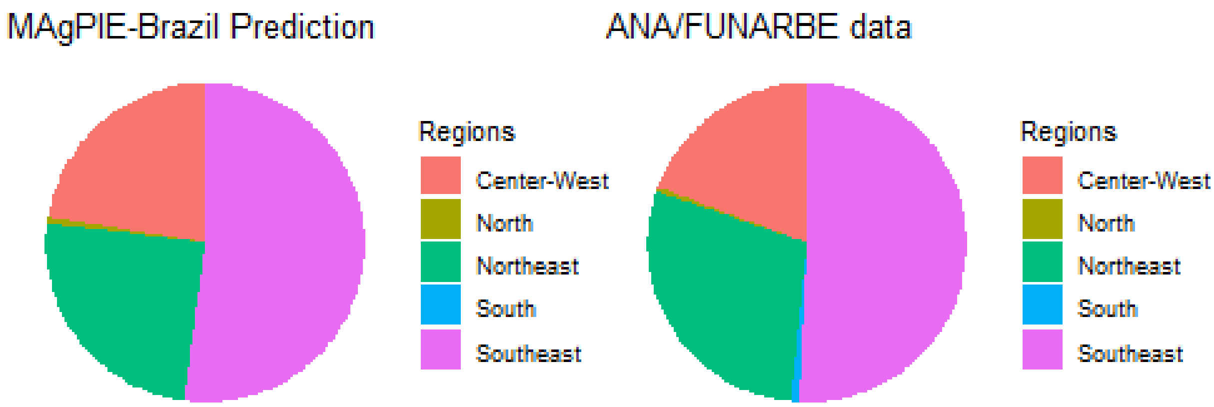


Figure 3.5 Regional share of water use for irrigation validation - 2015

CHAPTER 4
Biofuel policy impact on Brazilian water resources

4.1 Introduction

This chapter focuses on the effects on the Brazilian water resources of different political approaches regarding biofuel production. We focus on the trade off between 1st and 2nd generation biofuels. The former has a simpler production process allowing the final product to be cheaper (in the case of Brazilian sugar cane it is also more efficient in terms of L/Ha). The later has the advantage of potentially competing less over land with food products, which is important in a scenario of great biofuel demand that could lead to higher food prices.

In countries where traditional sources of 1st generation fuel are not produced on a larger scale, efforts to encourage the development of advanced biofuels are already in process. The European union leads this discussion with its parlament and comission already trying to impose limits to the use of conventional biofuels [Digest, 2019]. For the Brazilian case an alternative to fulfill the growing demand for ethanol without compromising food production is the development of the Cane Energy crop.

This work, therefore, seeks to measure the impact on water resources (at each Brazilian region) of the adoption of advanced biofuels and, in case of Brazil, of Cane energy as an ethanol source.

4.2 Methods

Three scenarios are used in this analysis considering the policies discussed. All of them include currently active national policies that encourage the demand for biofuels. Future scenarios for socioeconomic variables such as GDP, population and trade are also fixed among the scenarios. The differences are entirely related to the possibility of 1st generation fuel production in the long run and the presence of cane energy. A more detailed description of each scenario is shown below:

- Baseline Scenario (BL) - 1G and 2G biofuels are allowed to be produced throughout the entire observed period. MAgPIE-Brazil chooses the most efficient source of fuel based on the region's characteristics and the opportunity cost of producing that crop. This scenario does not consider the existence of cane energy.

- Advanced Biofuels Scenario (AB) - Demand for 1G biofuel reaches its maximum by 2020 and then starts to decline until it is zero in 2040. This forces the model to choose between the most efficient energy tree or grass as source of bioenergy. Cane energy is also nonexistent in this scenario

- Cane Energy Scenario (CE) - Similar to the Baseline scenario, there is competition between 1G and 2G sources but all the sugar cane used for ethanol production is assumed to be of the cane energy variety. I assume cane energy has higher processing yields than sugar cane (more ethanol is extracted from a similar amount of dry matter) and has a more expensive process to produce ethanol. It is also assumed that both have similar water demand, although robustness tests were conducted regarding this last assumption.

All Scenarios are also equivalent in terms of water availability, climate, soil type and irrigation efficiency. No climate change is considered in the period and, despite international trade is allowed, trade costs stimulate self sufficiency when possible (less productive areas inside the region become more attractive than importing from foreign regions as in this case trade costs need to be paid). Given the debate on whether food crops should be used to produce energy (and if this has significant impacts on food prices) [Hélaine et al., 2013] and [Hamelinck, 2013] and the development and productivity increase of advanced fuels, all scenarios represent plausible futures, depending on the policy chosen by the states on how to attend the biofuel demand.

The basic hypothesis is that each country may choose one of the two following policies: freedom to produce either 1st or 2nd generation fuels throughout the entire period (at risk of increasing food prices); and phase out 1st geneneration production having it completely replaced by advanced fuels by 2040 (and in the process, accepting high fuel prices).

In order to simplify and make the analisys possible I consider the two extreme cases where all the world decides to follow the first or the second biofuels policies. When applied to the real world, this method gives us the tendency if more and more countries decide on one policy or another.

For Brazil, other assumptions had to be made to allow the introduction of cane energy as development of advanced biofuels is still recent and information regarding its large scale production is scarce. In this work cane energy is assumed to demand the same amount of water per hectare as sugar cane, altough sensitivity tests were made considering the possibility of a higher and a lower water demand. Productivity of all new biofuel developments, like alternative fuels and Cane energy are assumed to be increasing over time at a fixed and exogenous rate.

The assumption that the levels of global integration and mitigation efforts will follow the same path in all scenarios considered in this chapter is important as these are the determinants for MAgPIE-Brazil‘s future scenarios. I consider that the world will keep in an intermediately integrated path, with moderate challenges to cooperate. Regarding the climate, no climate change is assumed to happen in our period of interest. This is done to isolate the mid and long term effects of the policies studied

Sugar cane production in MAgPIE-Brazil needs to fulfill its demand, which in turn, depends on the demand for all secondary products derived from sugar cane. Ethanol demand includes international demand projections based on current mandates from the most relevant importers, on the other hand, the demand for sugar, alcoholic beverages, and other subproducts of sugar cane is at global regions level (which also considers foreign demand but much more restrictively).

Given the production needed to attend the demand, the area chosen by MAgPIE-Brazil to produce sugar cane depends on the regional biophysical characteristics. The most productive areas are usually chosen first, although it is also taken in consideration the trade off between producing sugar cane or other crop that the area is also productive.

Another important point is the use of irrigation. If it is efficient, the model might equip an area for irrigation to increase productivity at the cost of paying for the irrigation equipment and the use water. Irrigation cost consists of an initial cost to equipp the area and an annual infrastructure maintenance cost. Similarly, MAgPIE-Brazil might also move production to less conventional areas if irrigation makes it productive.

4.3 Results

4.3.1 Sugar Cane Irrigated Crop Area

Figure 4.1 shows the results for the four time steps analysed in depth in our study. All significant regions, that is: Southeast, Center-West and Northeast, see an increase in the irrigated sugar cane cropland in the first period, however from 2030 forward only NE and CO keep their irrigated crop area growth. The Southeast stabilizes (and even decreases in the AB scenario) in terms of area while NO and SU have insignificant changes regarding sugar cane production.

An important factor that determines this growth is the general reduction of rainfed crops which are gradualy replaced by irrigated production. In the short run this happens even in the Southeast, a region where today's rainfed production is already efficient and which the higher yields from adopting irrigation might not compensate the cost to equipp the area for it.

This replacement can be explained both by the demand growth (not only of sugar cane but also of other crops that compete for land with it) which increases the need for more cropland, and also by the decrease in the cost of equipping an area for irrigation (This cost is assumed to be leveled over time because of technological spillover among regions and economic growth).

The increase in the importance of irrigation leads to the growth of the Northeast's share of land in the total. The region today, being least developed, has large areas not available for irrigation in an environment that would be favorable to sugar cane cultivation. Similarly, the Center-West also sees a growth in its share since the Southeast has few available lands to expand and sugar crops compete with pastures and other crops.

From figure 4.2, the 2030 results can be compared with projections made by [atl, 2017] for that year. In terms of irrigated crop area both behave similarly as [atl, 2017] considers a 35% growth in sugar cane irrigated area from 2015 while in MAgPIE-Brazil the growth is 49%. Besides that, [atl, 2017] allocates this new production mainly to the SE and CO regions followed by the NE, same as MAgPIE-Brazil for the 2030 time step.

For Brazil in general and for the SE and CO regions in the first time step, the scenarios with restrictions to traditional ethanol (AB and CE) lead to a reduction in the cane cultivated areas. When 1st generation fuel has no demand the nationwide reduction in sugar cane land is of almost 40% in 2060. The Northeast region, on the other hand, does not see a similar reduction,

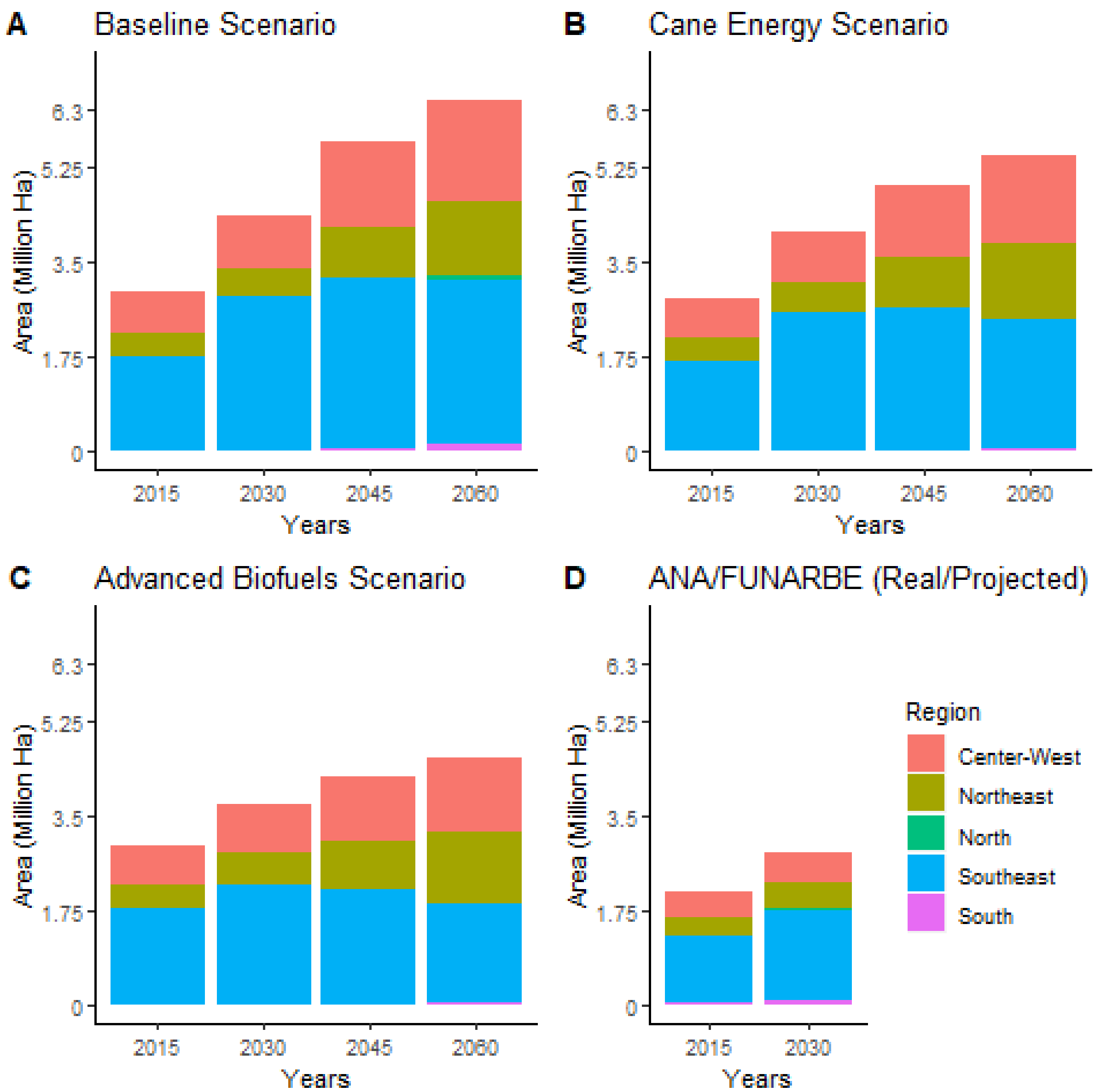


Figure 4.1 Sugar cane irrigated crop area at each scenario and the role of each region

with its irrigated crop area higher when cane energy is included.

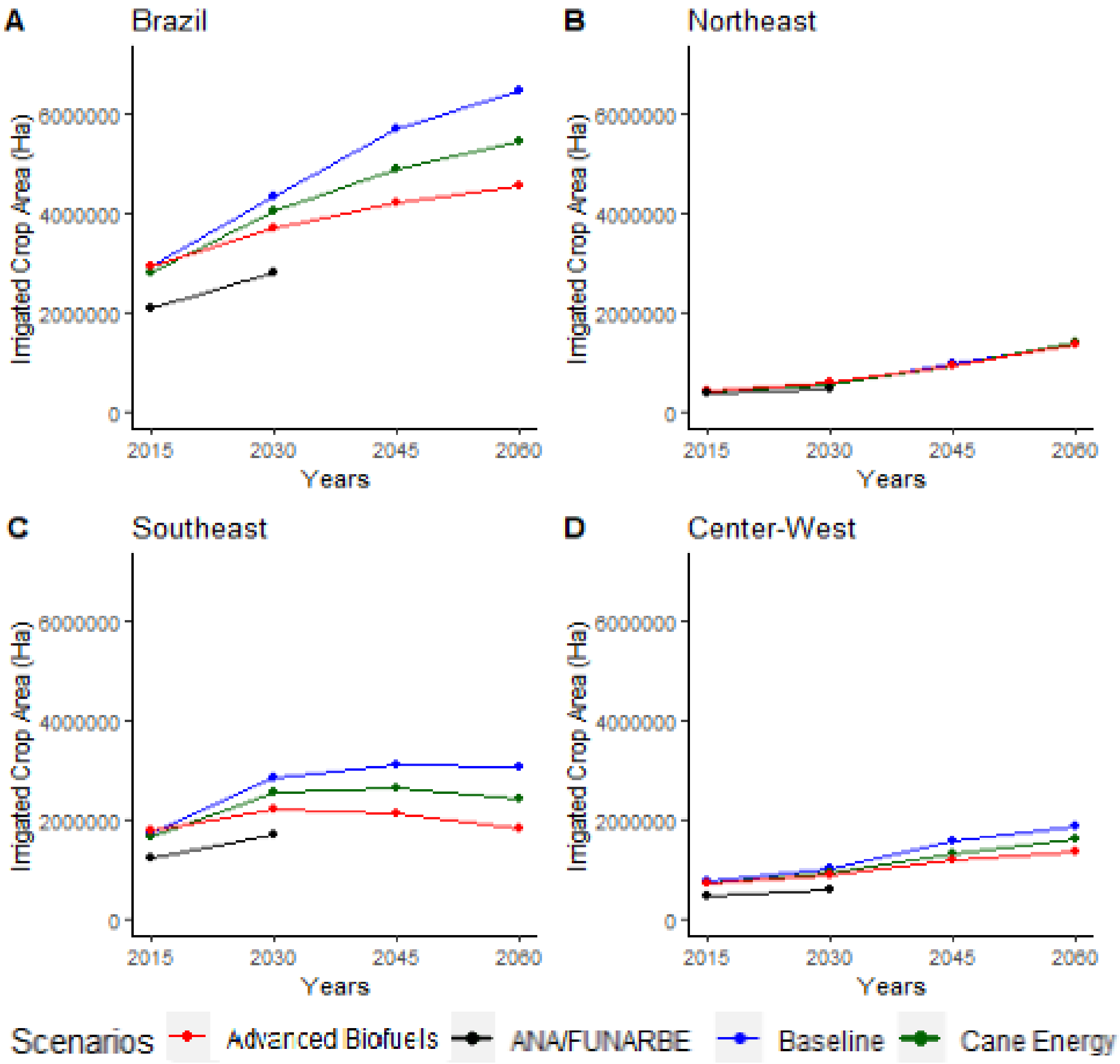


Figure 4.2 National and regional evolution of sugar cane irrigated crop area at each scenario

The main reason for the difference in how the Northeast behaves is the productivity of its irrigated land. As sugar cane adapts very well to warm environments, if enough water is given, the crop can grow in the NE region very productively, while most other crops woudn't do so well. As MAgPIE-Brazil sees it as one of the most sugar cane productive regions of the country and no other crops can easely replace it, it finds more efficient to allocate to this region than to the others when there is less demand.

This can be seen in figure 4.3 as the new production area of the Northeast centers around the São Francisco River basin, the larger water source for irrigation in the region.

Figure 4.4 shows explicitly how sugar cane irrigated areas evolve differently among the scenarios by 2060, verifying our previous discussion.

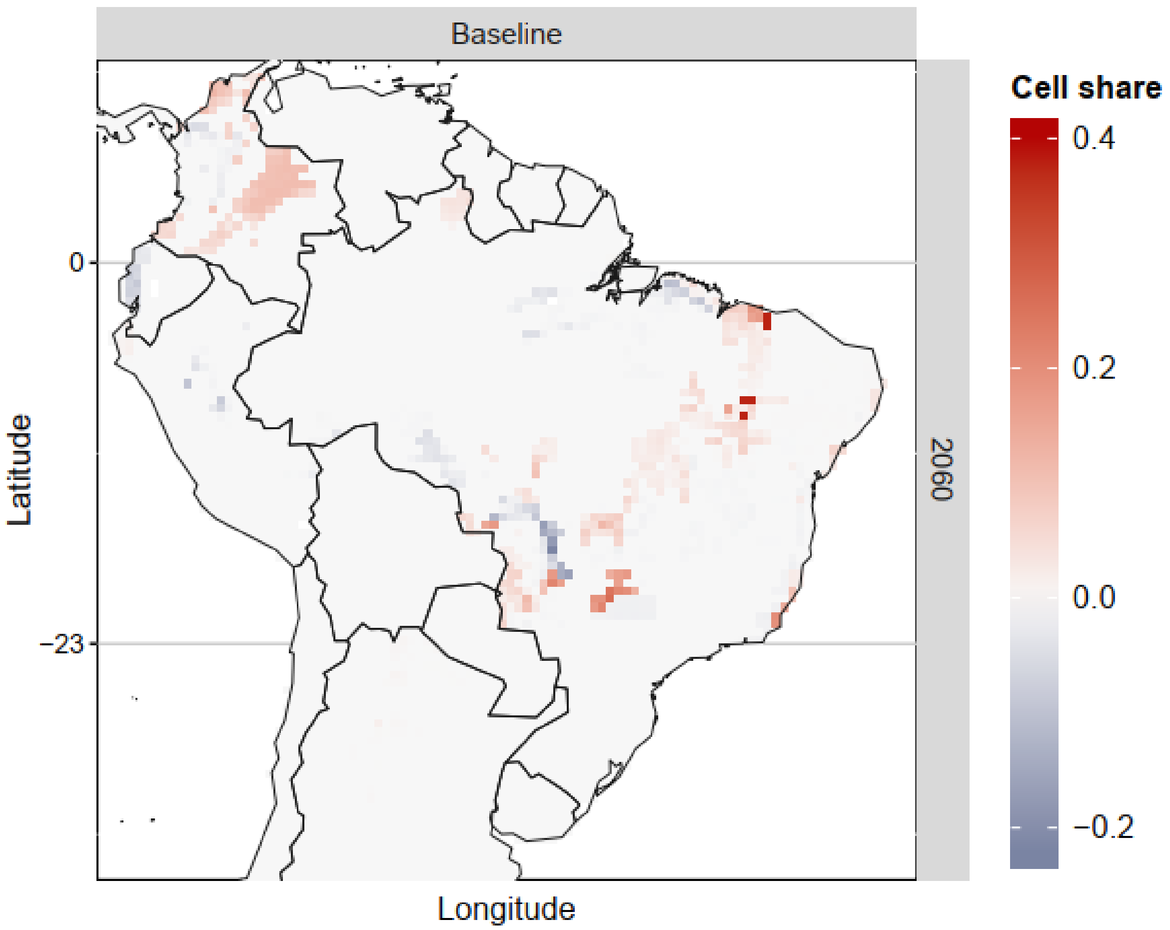


Figure 4.3 Variation (%) of sugar cane irrigated crop area in the Baseline scenario from 2015 to 2060

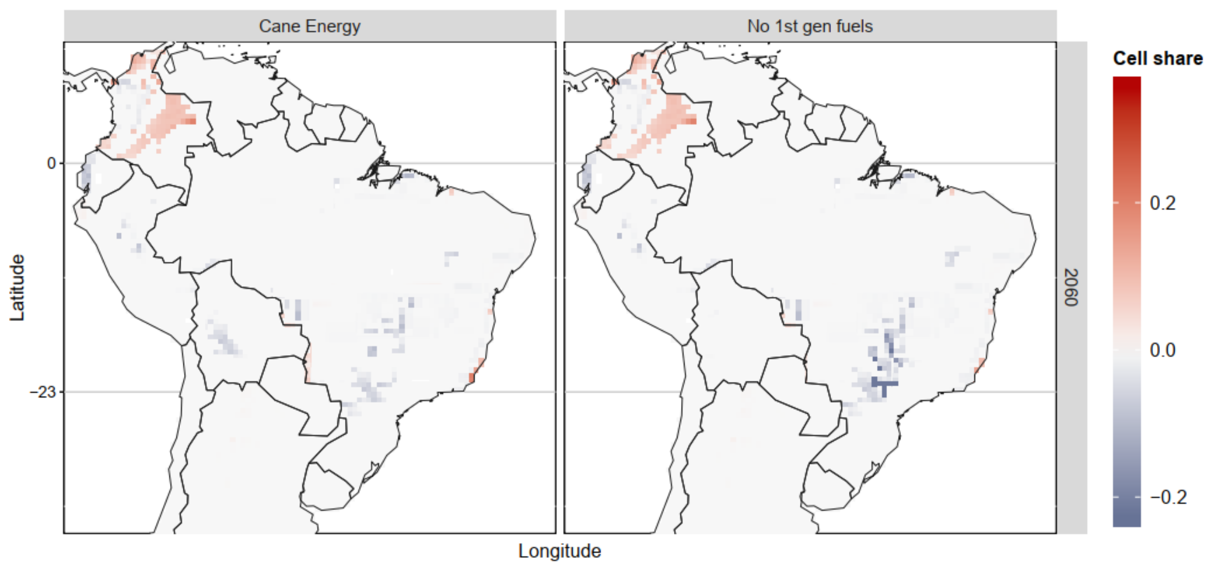


Figure 4.4 Irrigated sugar cane crop area: Difference (%) to the Baseline scenario in 2060

4.3.1.1 Discussion

A conclusion that can be taken by looking at crop area results is that, for Brazil in general, there is a tendency to replace rainfed with irrigated areas. This trend can be in part explained by the increasing ethanol demand (proof is the comparison of the three scenarios, where the less sugar cane is required to produce ethanol, the smaller its irrigated crop area is), which requires a productivity increase as Brazil responds to a significant part of the world demand.

Proportionally, the regions of Northeast and Center-West see a higher increase in the irrigated crops than the Southeast, the larger producer. This happens because the cost reduction to equipp and area for irrigation enables production in formerlly marginal areas (Tests with stable costs have shown that, in this situation, production area expands around 40% less in the 2030 and 2045 time steps in the Semi-Arid region and up to 75% in 2060). This areas (highlighting the Sao Francisco River Basin in the NE), when irrigated, have high levels of productivity due to their climate and soil characteristics becoming important sugar cane producing areas.

The Southeast, already having high levels of rainfall, doesn't benefit the same way from irrigation, so for MAgPIE-Brazil it is more efficient to use this area to produce other cultures that require less water and do not get along with warm areas in the CO and NE regions.

These projections are in conformity with Assad et al. (2008) projections of the years from 2015 and 2030, which also observe an increase in the use of areas that are currently not used for sugar cane production (that happens because other crops are relocated to colder areas due to climate change, while sugar cane, if irrigated, resists the warm climate). In accordance with this work, the drier areas also become highly productive if enough irrigation is provided. The difference is that, unlike our results, the Center-West has a more significant role than the Northeast (According to Assad et al. (2008) The semi arid part of the Northeast, as well as to cost, also become more attractive to irrigated sugar cane but the Center West sees an even sharper increase). It is important to stress that the authors does not include water use related constraints, while considers the effect of climate change on the crops. This is also in line with Beck (2013) and Kölling (2014), who predict an increase in sugar cane crop area in the São Francisco River Basin through the use of irrigation.

4.3.2 Sugar Cane Water use

Blue water used in the irrigation of a crop is determined both by the rainfall level of the area and the water needs of that crop. Sugar cane, for instance, demands a higher amount than most crops which makes the model more succetible to use irrigation in its production. In the case of sugar cane, as it behaves better in warmer areas than most crops, it is one of the best alternatives for the model to allocate in warmer and drier regions that can be equipped to irrigation, such as some parts of Brazil (some of those areas are already starting to be irrigated in the real world such as Juazeiro (BA), the largest irrigated area of sugar cane (21 mil ha) all over the world).

As this chapter only studies the effect of the different demand levels, no climate change is assumed and thus natural variables such as the water needs of the crops, rainfall levels, blue water availability and temperature do not change throughout the scenarios.

As irrigation replaces a great share of current rainfed production water use increases significantly in the period. From 2015 to 2060 the national usage increases 160%, from 14.80 to 38.48 km³/years. The increase is most proeminent in the NE and CO regions as the majority of newly irrigated areas are allocated in these regions. In 2015 the SE was responsible for 52,16% of total use while NE and CO had 24,75% and 22,40% respectively. By 2060 these percentuals are 30,97% for SE, 36,45% for NE (then the largest user for this purpose) and 29,14% for CO. Figure 4.5 shows the detailed evolution of water use and how it distributes among the regions.

As discussed previously, the irrigated areas where the model expands in the NE are semi-arid with warm temperatures and reduced rainfall levels. This means these newly cultivated areas demand large amounts of water making the water use increase to be proportionally higher than the irrigated crop area increase shown before.

Again our projections are in line with the [atl, 2017] expectation for 2030. The publication foresees an increase in total withdraw of around 40%, close to our 59% result. Another important similarity is that both predict the three main sugar cane producing regions (NE, SE and CO) present similar levels of water use growth from 2015 to 2030.

The substitution of rainfed for irrigated areas is higher in the Baseline and Cane Energy scenarios which have a higher demand for cane. The Northeast continues to be the exception, with similar values for both scenarios, as MAgPIE-Brazil immediately allocates the growing demand of cane to the NE´s newly available areas.

In all scenarios the NE becomes the largest user of water for sugar cane production, followed closely by SE and CO in the Baseline scenario and by the SE in the Cane Energy scenario, see figure 4.6. It is interesting to note that there is a proportionally greater difference in the Center-West water use than in its irrigated crop area when the Baseline scenario is compared with the other two scenarios. An explanation for this is that in the Baseline scenario (where more sugar cane is demanded to produce ethanol) irrigated production needs to be allocated to drier areas of the Center-West with higher water needs, while in the other scenarios this is not required.

As was discussed in the previous section, the model intensifies the use of irrigation to attend the growing demands while also keeping intact the protected areas of some of the Brazilian forests. This leads to an increasing amount of water to be used in the Northeast as the requirements in the region are higher due to low rainfall levels.

By 2060, while the NE corresponds to only 21% percent of sugar cane irrigated crop area, it responds to more than 36% of water usage. Table 4.1 shows this discrepancy among regions in terms of the amount water used per irrigated hectare in the Baseline scenario.

Table 4.1 Water used per irrigated hectare - Baseline scenario (Km³/Mio HA)

Region	2015	2030	2045	2060
Northeast (NE)	8.53	9.32	10.02	10.35
Center-West (CO)	4.6	4.98	5.28	4.87
Southeast (SE)	4.39	4.38	4.36	4.44

Source: Own elaboration

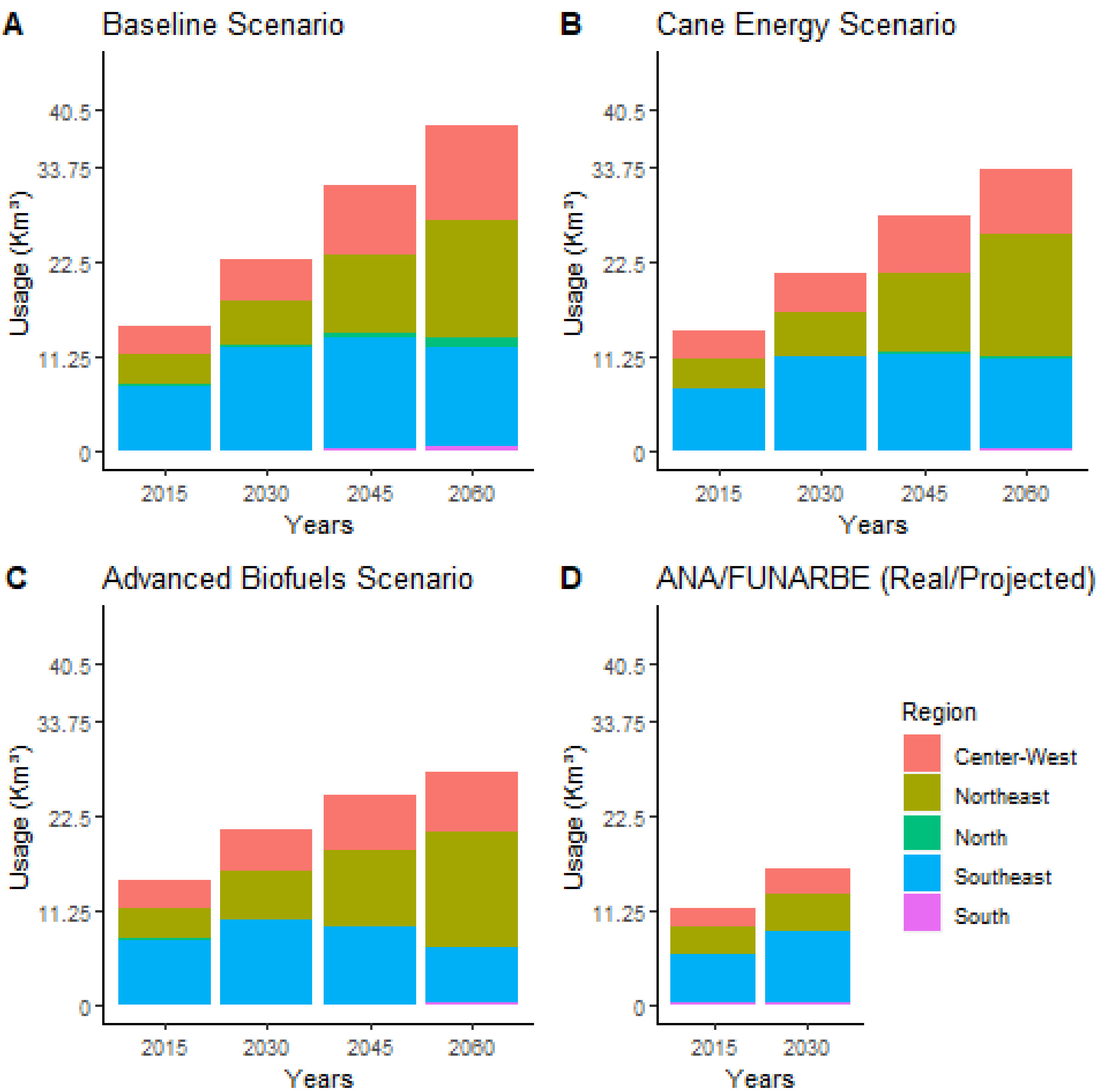


Figure 4.5 Water used for sugar cane irrigation at each scenario and the role of each region

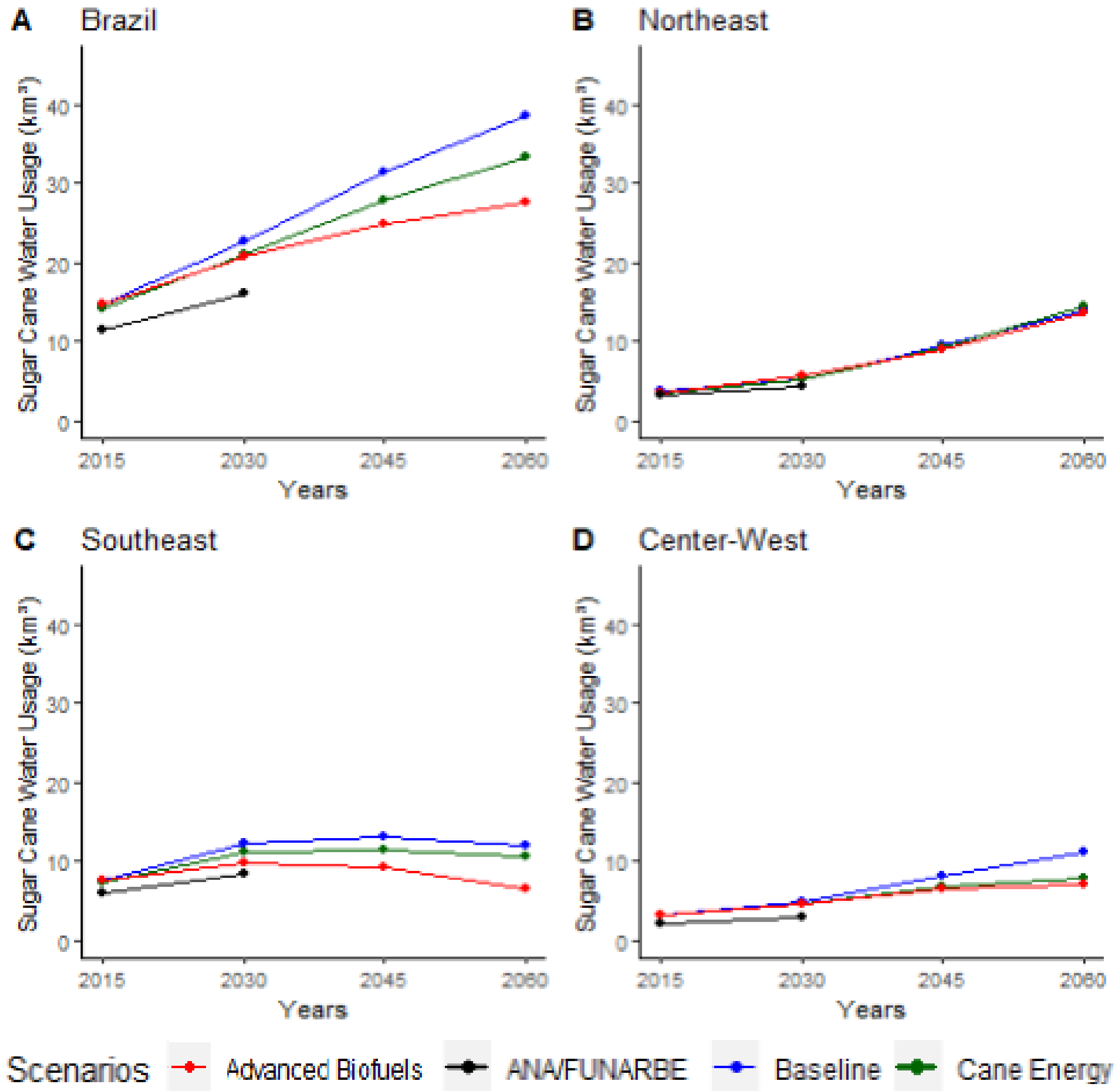


Figure 4.6 National and regional evolution of water used for sugar cane irrigationat each scenario

4.3.2.1 Discussion

Findings on water use are similar to the crop area section conclusions: While Brazil as a whole sees an increase in water use through all scenarios, the regions of Northeast and Center-West see a more sustainded increase while the Southeast has more modest results (even reducing use in the long run in the Advanced Biofuels scenario). The new producing areas in the drier regions require significantly higher levels of water as their rainfall is very irregular.

Looking at the scenarios, the Baseline uses more water in all future time steps for Brazil and the Southeast and center-West regions. In the long run, those same areas use more water in the Cane Energy scenario than in the AB scenario. This shows that, for the regions of SE and CO, the reduction in the ethanol demand lead to a reduction in water expendings.

For the Northeast, on the other hand, cultivation is not reduced throughout the scenarios. The reason, again, is the large productivity of the region when the crop is irrigated. These high productivities when water is available make the NE one of the "first choices" of the model to allocate new sugar cane production. Another important factor is that, due to the region´s dry climate few other crops behave well, even if irrigated, in most of its area[1]. The absence of competition makes more likely for sugar cane to be allocated there.

Nationally, in the long run, the scenarios AB and CE lead to less water use then the BL, although usage grows in any case because of the other sugar cane derived products.

4.3.3 Total land and water use

This section is intended to demonstrate how the total Brazilian land and water resources are to be affected by the sugar cane market according to the MAgPIE-Brazil projections.

According to data from ANA/FUNARBE sugar cane corresponds to around 15,27% of total crop area (irrigated or rainfed) and 47,03% of total water used for irrigation in the year 2015. MAgPIE-Brazil estimated for the same year that sugar cane is responsible for 21,82% of agricultural land and for 62,35% of the irrigation water. This discrepancy in the total water share of sugar cane is explained by MAgPIE-Brazil‘s tendency to use only green water unless it is efficient to increase the productivity through irrigation (so most other crops are treated as rainfed while they are irrigated in the real world).

Regarding other crops, MAgPIE-Brazil mainly uses green water except for a few irrigated pockets [2] in the South and Southeast regions. The most significant users of water resources in the analyzed period, besides sugar cane, are maize and soybeans.

MAgPIE-Brazil projections for irrigation of other crops are not as well validated as sugar cane. This leads to a much higher share of sugar cane in total water used than in reality. This difference, however, is not caused by overestimations in the sugar cane use but an underestimation in other crops water amounts. As this study does not focus on other crops, the fact that the model underestimates their water usage in the short term may be considered acceptable.

[1]It is important to keep in mind that throughout this chapter I do not consider climate change, so factors such as rainfall levels, temperature and soil characteristics are kept constant in the future

[2]These irrigated pockets are small areas where production of maize, soybeans and mainly rice use irrigation to complement water needs and, thus, enhance productivity.

The share of sugar cane in total agricultural land falls over time until reaching 16,93% in the Baseline scenario by 2060. This can be explained by the growing soybean and corn production in the South and Southeast regions. As was said before, the percentage of sugar cane in the total blue water used for irrigation decreases over time due to increasing use of irrigation in other crops.

4.3.4 Use of irrigation in the sugar cane production

Another important variable to look at is the proportion of sugar cane production in which irrigation is used. Looking at the individual regions in table 4.2 it is clear that irrigation gains importance over time in the Northeast and Center West, while its use in the southeast stops at around 40% of the production. This tendency is followed closely by the other two scenarios, reflecting the general trend to replace rainfed areas with irrigation.

Table 4.2 Share of irrigation in total sugar cane production - Baseline scenario

Region	2015	2030	2045	2060
Northeast	38,88%	45,72%	58,48%	65,23%
Southeast	31,49%	40,52%	40,97%	38,77%
Center West	32,92%	36,09%	45,79%	47,59%

Source: Own elaboration

4.3.5 Water Shadow Price

Water shadow prices, that is, the reduction in total costs that an extra unit of available water would generate, depends both on the water availability, and the demand for the products that could be irrigated by that extra unit. Taking our case study as an example, if ethanol has a higher demand, more areas with less productivity are being used, so extra amounts of water available in good lands would create more gains by receiving this production.

As it is a measure of the value of an extra amount of water, shadow prices are the best variable to measure water scarcity and water economic value in MAgPIE-default. Drier regions which use their water resources to irrigate become more water scarce and that is reflected in higher water prices.

Our Baseline results in Figure 4.7 show growing water prices in all regions, which represents an increasing water scarcity. The Northeast sees the most significant growth in water scarcity, followed by South and Center west. The Southeast does not suffer from scarcity at the same magnitude although water prices also increase. The north keeps negligible values during the whole period (As the region is very abundant in water and most of its area is covered by the Amazon, which makes it difficult to produce crops, irrigation does not advance significantly).

From figure 4.8 CE scenario has the effect of increasing water value in the northeast when compared to the other scenarios. The reason this happens, despite less dry matter is needed to produce the same amount of fuel, is because cane energy ethanol is much more expensive than

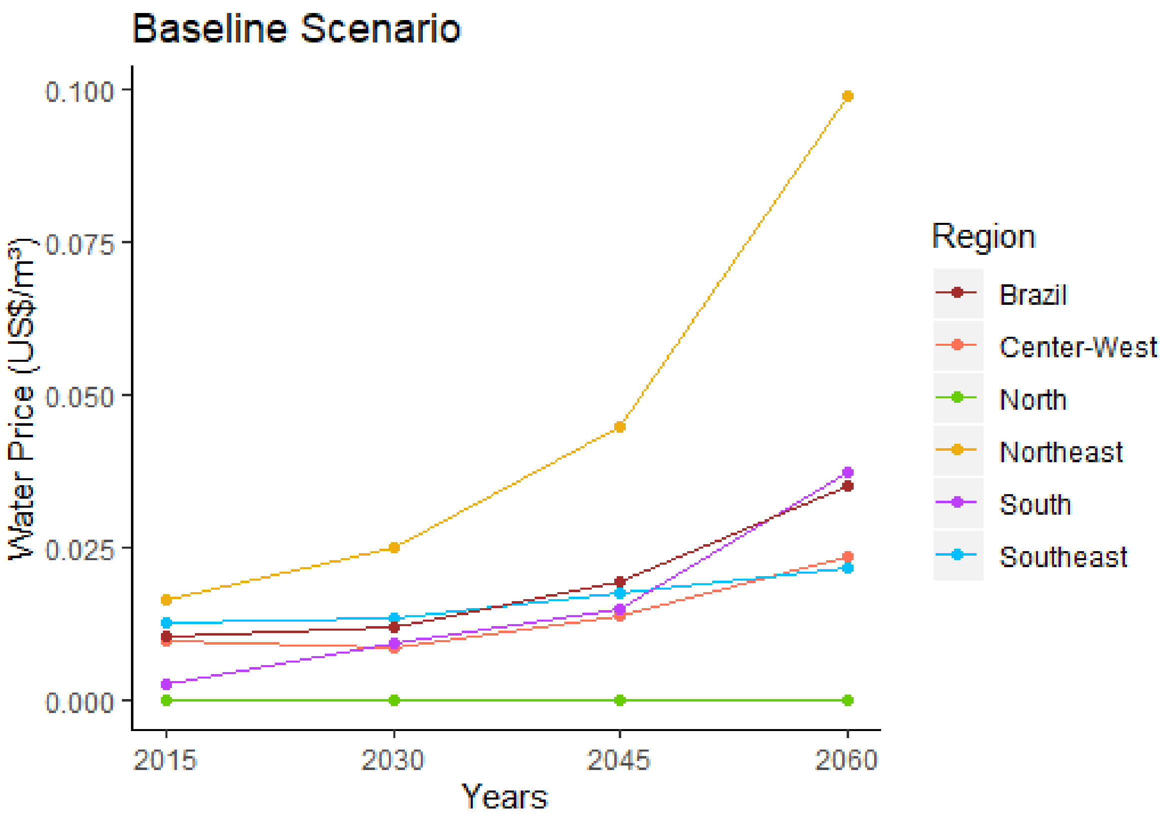


Figure 4.7 Water Shadow Price Baseline scenario

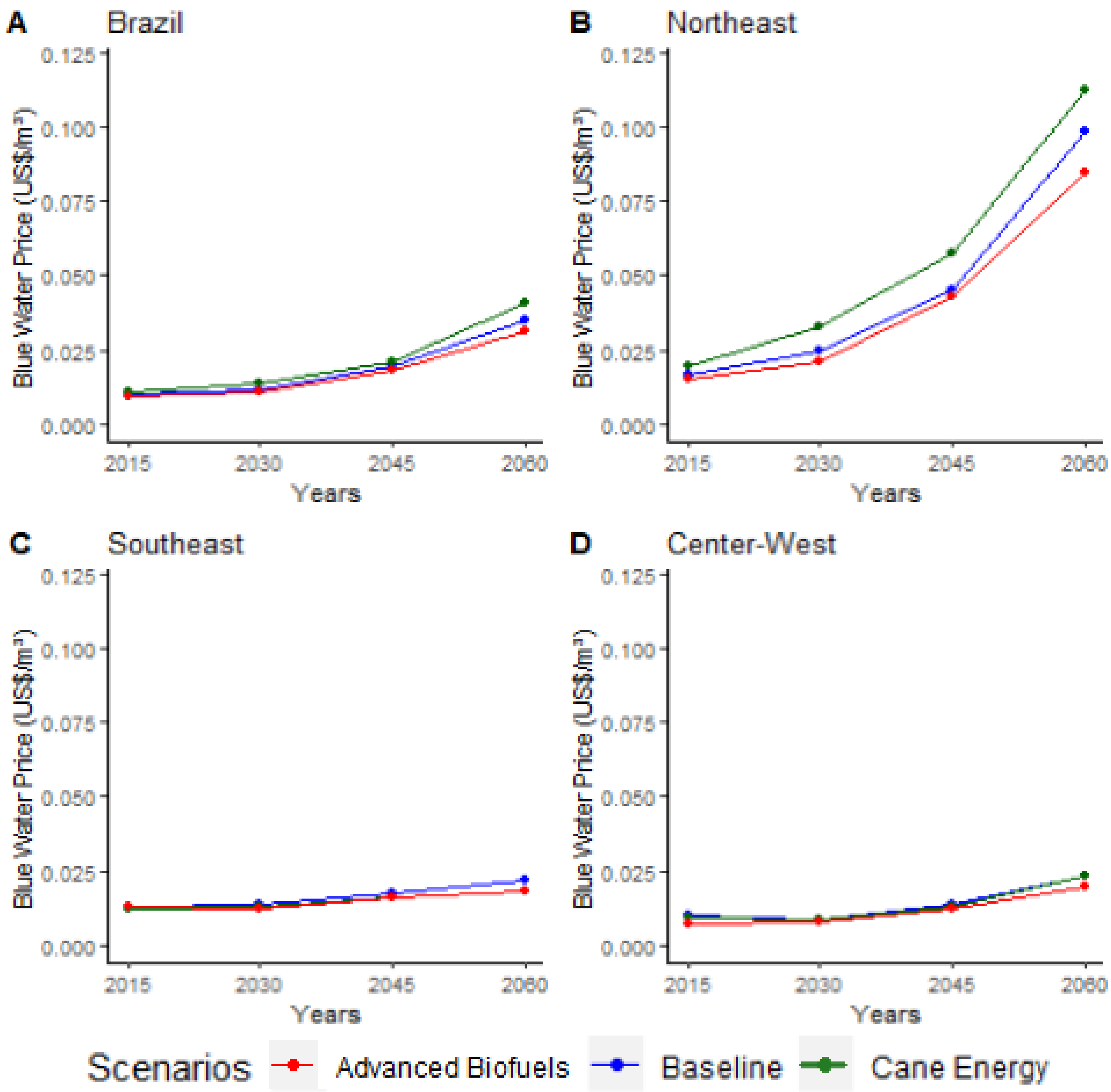


Figure 4.8 National and regional Water Shadow Prices

traditional ethanol, increasing the gains provided by an additional unit of water available.

As the Northeast has some of the most sugar cane productive areas under irrigation, and I assume cane energy consumes the same amount of water than traditional sugar cane, the region does not see a significant reduction in irrigated area. Thus the effect of ethanol price makes the water more valuable even when the comsumption doesn't increase as much

In the other regions, the "less cane effect" (that is, the reduction in water prices due to less sugar cane production being demanded in that region) is larger than the "more expensive ethanol" effect, explained earlier, so water prices are lower in the Cane Energy scenario.

The cease in all sugar cane derived fuel production from 2040 onwards (Advanced Biofuels scenario) has a significant effect in the reduction of water scarcity. In the long run the water price reduction in the NE region is of 14.32% when compared to the Baseline scenario and 24.62% relative to when cane energy is produced. In the other regions the reduction is smaller but also present, 16.74% and 1.65% in the Southeast and 17.52% and 15.72% in the Center-West comparing to the Baseline and Cane Energy scenarios respectively.

4.3.5.1 Discussion

Scarcity in Brazil, as measured by water shadow price, increases in the long run in the Baseline scenario. After growing only 89.32% until 2045, national shadow prices grew 239.81% until 2060 mostly driven by irrigated sugar cane in the Northeast and other crops in the South. These two regions present the most solid increases in water prices growing in all considered time steps. The CO and SE also have increasing scarcity although only in the former this can be mostly associated with sugar cane (the SE besides not increasing its water use in irrigated sugar cane, also expands production of irrigated maize and soy)

The NE region, which owes this rise to the increasing ethanol demand, sees its water economic value multiply by 6 in the analyzed period. The region, specially the São Francisco River basin where most of the new irrigated crop is allocated, already suffer from water stress due to the low precipitation levels of the region. Water scarcity is one of the most significant causes of underdevelopment in the Northeast of Brazil and has been a challenge to policy makers for more than half a century [Martins and Magalhães, 2015].

When the three scenarios are compared the general conclusions do not change. Northeast (almost completely driven by sugar cane) and South (because of increasing irrigated soybeans and, in a lesser scale, maize) lead the Brazilian rising water prices. The CO and SE also observe increases but less significantly.

The comparison brings us to two important considerations. First: the Cane Energy scenario increases water prices in the NE even though the water used in the region does not alter the same way. This happens because cane energy ethanol has a higher production cost which elevates its price. That higher cost makes an extra amount of water in the producing region more valuable as it can produce a more valuable output, elevating the shadow price. The other regions do not see a similar behaviour because the NE is the only one where replacing sugar cane with cane energy does not lead to less water used in this crop.

The second conclusion is that eliminating first generation ethanol demand after 2020 in Brazil will bring down water scarcity in the Northeast and, in a lesser scale, in the Center-West regions (The other regions have the option to irrigate other crops, while the NE does not). As was already discussed the drier regions, where the model begins to allocate irrigated sugar cane production as demand rises, see their scarcity grow in the long run.

4.3.6 Conclusion

The present chapter allows us to forecast the behavior of the sugar cane industry in Brazil given the current global context and its effects on water resources. Furthermore, it also allows us to compare those effects under different global pathways regarding first generation biofuels (the flagship of Brazilian biofuel production).

The main conclusion that can be taken is that there will be an increasing use of irrigation in sugar cane cultivation in Brazil until 2060. This increase is driven by growing demand of most sugar cane derived products, simulated in all three scenarios. To fulfill it, the model replaces large areas which are currently rainfed with irrigated production and turns marginal regions into irrigation equipped areas (mostly in the drier parts of the Northeast and Center West regions) augmenting both area and water use. This expansion at the same time makes the country the largest biofuel producer in the world and aggravates water stress in some of the areas where it is less available.

Looking at the individual regions in the Baseline scenario the most interesting outcomes are the growing importance of the Northeast, region that becomes the largest water user in the long run even though its land share is only 21% of the total irrigated sugar cane area in Brazil; and the stagnation of the Southeast from 2030 forward (caused by compatition with other crops and abundance of green water, which encourages rainfed production).

When the scenarios are compared, two main results stand out. First: the reduction in water scarcity, for all regions, when the policy of replacing traditional ethanol with advanced biofuels is put into practice. In this scenario, Brazil needs less sugar cane area as its fuel comes from energy crops (which are not produced in water scarce areas). Second: The counterintuitive effect in the Northeast region of an increasing water price when cane energy crop is available.

These results show that simply replacing sugar cane ethanol with a more productive crop that, however, has no lower water demand such as cane energy, does not reduce shadow prices in the drier areas used to produce cane. To achieve a hypothetical objective of lowering water prices, and thus reduce scarcity, it would be necessary to discourage demand for all cane based fuels.

Realisticaly, any proposed policy regarding water resources needs to take into account local water management and planning by adequately valuing water resources, especially with collection values and other economic instruments This is an important strategy to prevent water-scarce regions from becoming scarcer due to international and national demands. Biewald et al. (2014) shows this exact impact of international trade, where exports of irrigation intensive commodities may lead to water exports without proper valuation on scarce regions. To avoid such misvaluations, global trade effects must be considered in the local resource management process.

The last important result regards fuel prices in each scenario. Although I assume advanced fuel production (including cane energy) is developing over time, ethanol prices in Brasil are significantly higher under both scenarios that restrict traditional fuels (AB and CE). When compared to the Baseline prices in 2060, cane energy ethanol is 83.33% higher while advanced fuel price on the Advanced Biofuels scenario is 16.66% more expensive.

This chapter does not consider the existence of climate change and its possible effects on crop productivity and water demand. As most climatic scenarios for Brazil by Assad (2008) point to productivity gains of sugar cane in the Northeast due to high temperatures, this chapter‘s results could be underestimating crop growth in the NE and thus also underestimating water values in that region.

CHAPTER 5

Climate change impact on Brazilian water resources

5.1 Introduction

The impacts of climate change on both natural and economic systems are many and not negligible. Agriculture is still the most important activity in the economy of many countries and even emergent nations, such as Brazil, rely considerably on its agribusiness. Thus, reduced crop yields for major crops could affect deeply these countries income and food suplies [Diffenbaugh and Burke, 2019].

Because of these economic impacts, and the known environmental effects, it is reasonable to assume that mitigation measures will be taken by policy makers to avoid even worse effects. Actions such as afforestation and avoiding deforestation to reduce GHG emisions are examples of mitigation measures which are already running in some regions [Zanchi et al., 1950]

In this context, knowing that different levels of climate change mitigation efforts can strongly impact the demand for sugarcane-derived ethanol and, consequently, the demand for water resources in Brazil, it is important to include such factors in our analysis. This chapter is intended to measure the effects of different climate-related pathways on Brazilian water resources, and focuses on how individual regions of the country are differently affected.

5.2 Methods

In this paper I use the Representative Concentration Pathway pathways (RCP) to represent the different possible mitigation efforts. The RCPs are four different pathways developed to provide information regarding how climatic variables could behave in the future. They are named according to its radiative forcing value in 2100: In RCP2.6 the approximately 2ºC warming target is achieved; both RCP4.5 and RCP6.0 consider a stabilization of radiative forcing; and RCP8.5 implies increasing radiative forcing [Moss, 2010].

MAgPIE-Brazil also uses the Shared Socioeconomic Pathways (SSPs) to describe the evolution of socioeconomic aspects of the world, considering both mitigation and adaptation efforts. Each SSP corresponds to a different level of challenges for mitigation and adaptation, ranging from a sustainable development world in SSP1 to high challenges in SSP3. In order to isolate only the climatic variables the SSP2 is used, which has a "business as usual" scenario, representing a continuation of the current socio-economic trends [O'Neill et al., 2014].

Some of MAgPIE-Brazil inputs adapt to each RCP scenario so that it is possible to reach that radiation level. Importantly to our study, biofuel demand is highly affected by the RCP choice, as RCP2.6 demands great reduction in fossil fuel use, which increases biofuel demand.

One more factor that needs to be considered before formulating the scenarios is the CO^2 fertilization. This is the increase in photosynthesis rate caused by a higher concentration of carbon dioxide in the atmosphere. This impact may have positive influence on plant growth and thus its productivity. There is, however, much uncertainty on the response to CO^2 fertilization in the long run for C4 plants (which include maize, sorghum and sugar cane)[1] so it is important to isolate its effect in our analysis [Kirschbaum, 2011].

Two scenarios (in addition to chapter 4 BL scenario) are studied in order to observe the aforementioned effects. The "Weak Mitigation" scenario use RCP6.0 as this is the closer to the current real world situation. In oposition to that, the "Strong Mitigation" scenario use RCP2.6, representing a future where the 2° celsius target is met. At the same time, both weak and Strong Mitigation scenarios feature versions with and without CO^2 fertilization. Table 5.1 summarizes the characteristics of each scenario. The Baseline, as it does not consider climate change, is used as reference scenario to isolate climatic effects.

Scenario Name	Configurations	Description
Baseline	No Climate Change	Equivalent to the Baseline scenario in 4
Weak Mitigation	RCP 6.0	Mitigation efforts are not enough to reduce radiative levels, although they also don't increase
Strong Mitigation	RCP 2.6	Large mitigation efforts are taken, succeeding to achieve the 2° target

Source: Own elaboration

Table 5.1 Scenario Description

In terms of model inputs, the most relevant differences from one scenario to another are: higher ethanol demand in order to decrease CO^2 emissions by reducing the use of fossil fuels; modified water requirements and crop yields caused by climate change; less available land due to higher afforestation (and stopping deforestation) efforts.

5.3 Results

5.3.1 Sugar Cane Irrigated Crop Area and Water Use

Figure 5.1 show that, for all scenarios, the role of the Northeast in national sugar cane production grows in the long run, specially in the Strong Mitigation scenario.

As was discussed previously, MAgPIE-Brazil has an inclination for raising irrigated area more than proportionally in the northeast because that region starts with large unequipped areas due to its socioeconomic characteristics. As sugar cane is productive and fits well in warmer temperatures if intensively irrigated, it is efficient for the model to turn those semi arid areas available for irrigation.

The Strong Mitigation scenario clearly increases the sugarcane irrigated area in all regions. Figure 5.2. Crop area is twice higher then in the Weak Mitigation scenario for the three main producing regions and even North and South begin to allocate relevant areas for sugarcane cultivation.

[1]C4 plants are those more efficient at photosynthesis in warm and sunny weathers

This happens because, as countries substitute fossil fuels for renewables, Brazil becomes producer of a significant share of global biofuels, specially sugar cane ethanol. The Strong Mitigation scenario already shows higher sugarcane crop area in the short term, however, as time passes, the difference between the scenarios increases to almost twice higher then the Baseline by 2060.

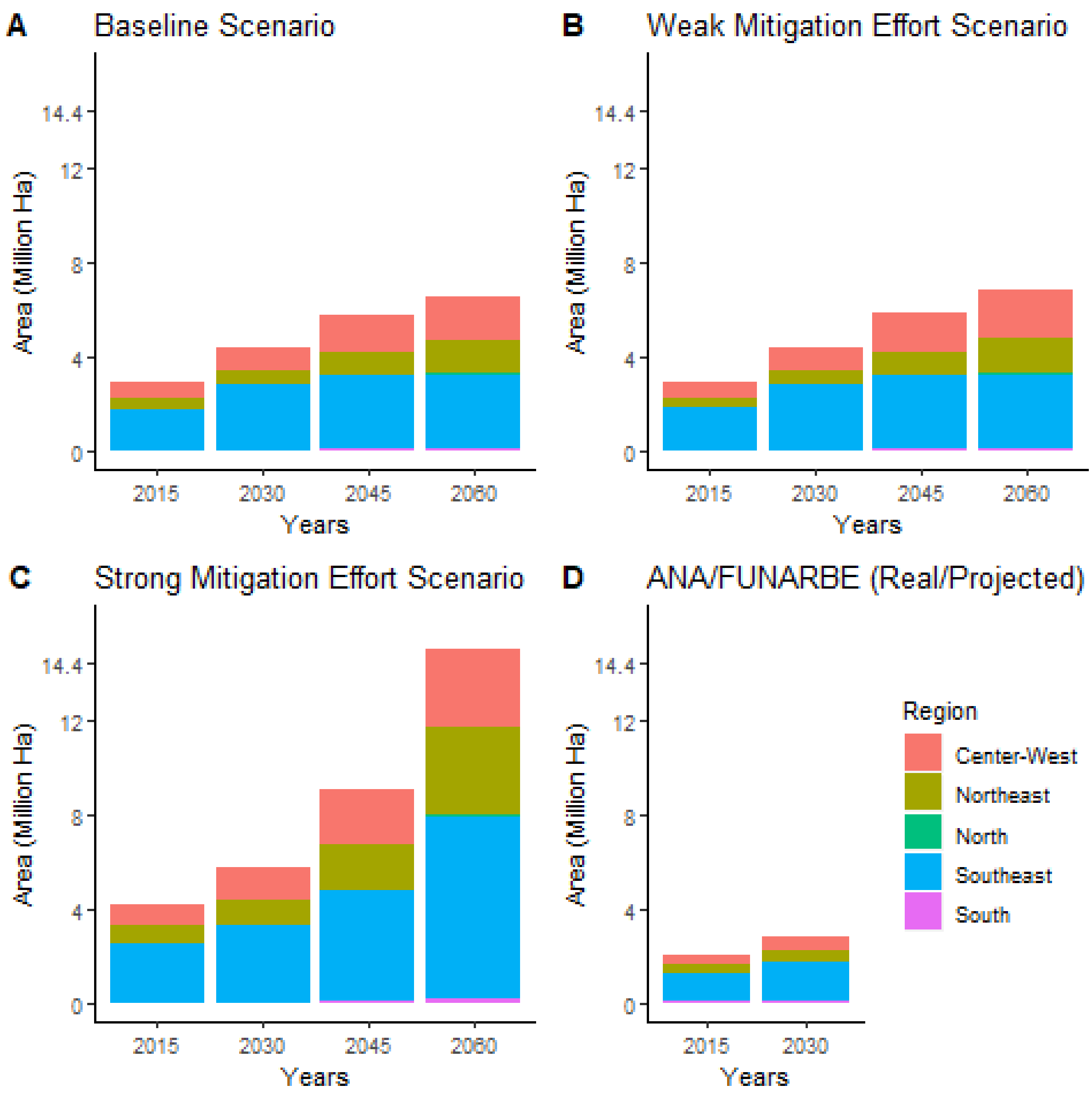


Figure 5.1 Sugar cane irrigated crop area at each scenario and the role of each region

Similarly to chapter 4 results, water use increases more than proportionally in the drier regions (Northeast and, in a much lesser scale, Center-West) due to its higher water demand for irrigation. Figures 5.3 and 5.4 show the results.

Water use is also higher in every region when mitigation is stronger but the growth is only

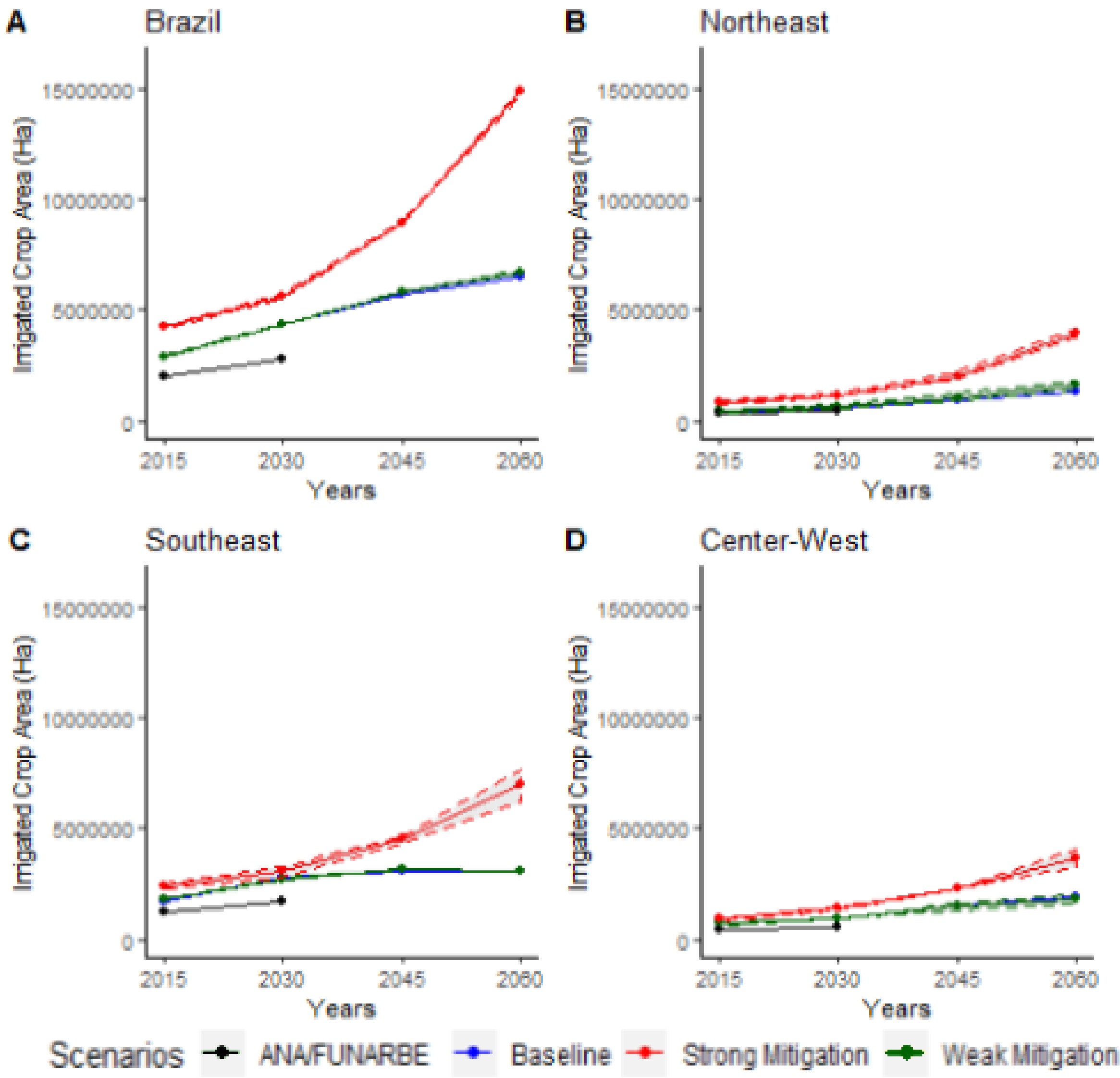


Figure 5.2 Evolution of sugar cane irrigated crop area with uncertainty range derived from possible CO² Fertilization

proportional to the growth in crop area in the Northeast. The other regions use more water but a large part of the new production is rainfed.

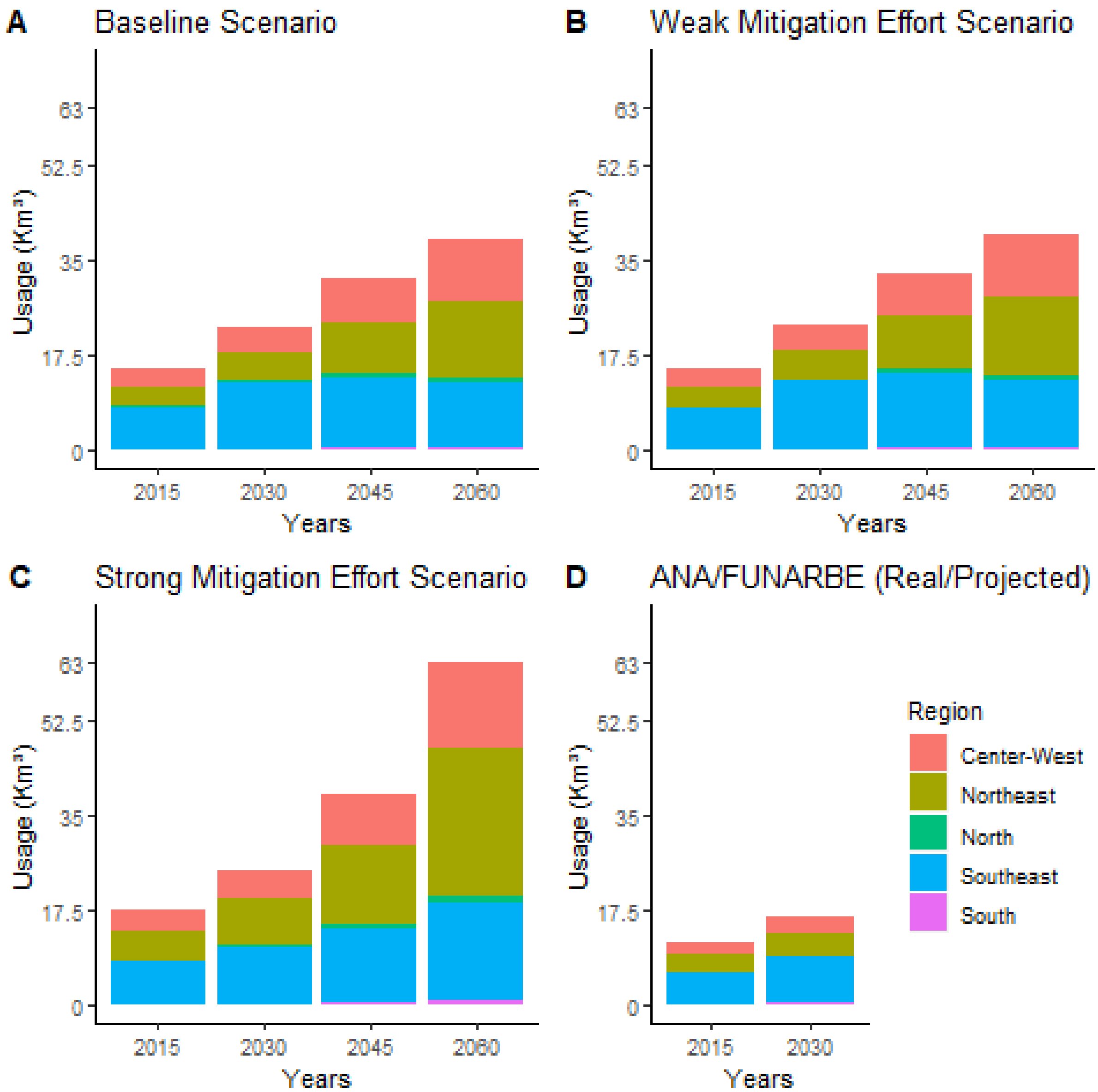


Figure 5.3 Water used for sugar cane irrigation at each scenario and the role of each region

Comparing the versions with and without CO^2 fertilization for each scenario, it is observed that, although there is an effect on cultivated area and water use, it is not significant neither in the weak nor in the Strong Mitigation case.

At country level, the effect of higher CO^2 concentration is a marginal reduction both in area and water use for sugar cane. The driest regions, however, differ from the whole country, with an equivalent irrigated area and more water used when CO^2 fertilization is considered. CO^2 fertilization theoretically reduces water demand to produce sugar cane. The reason it elevates

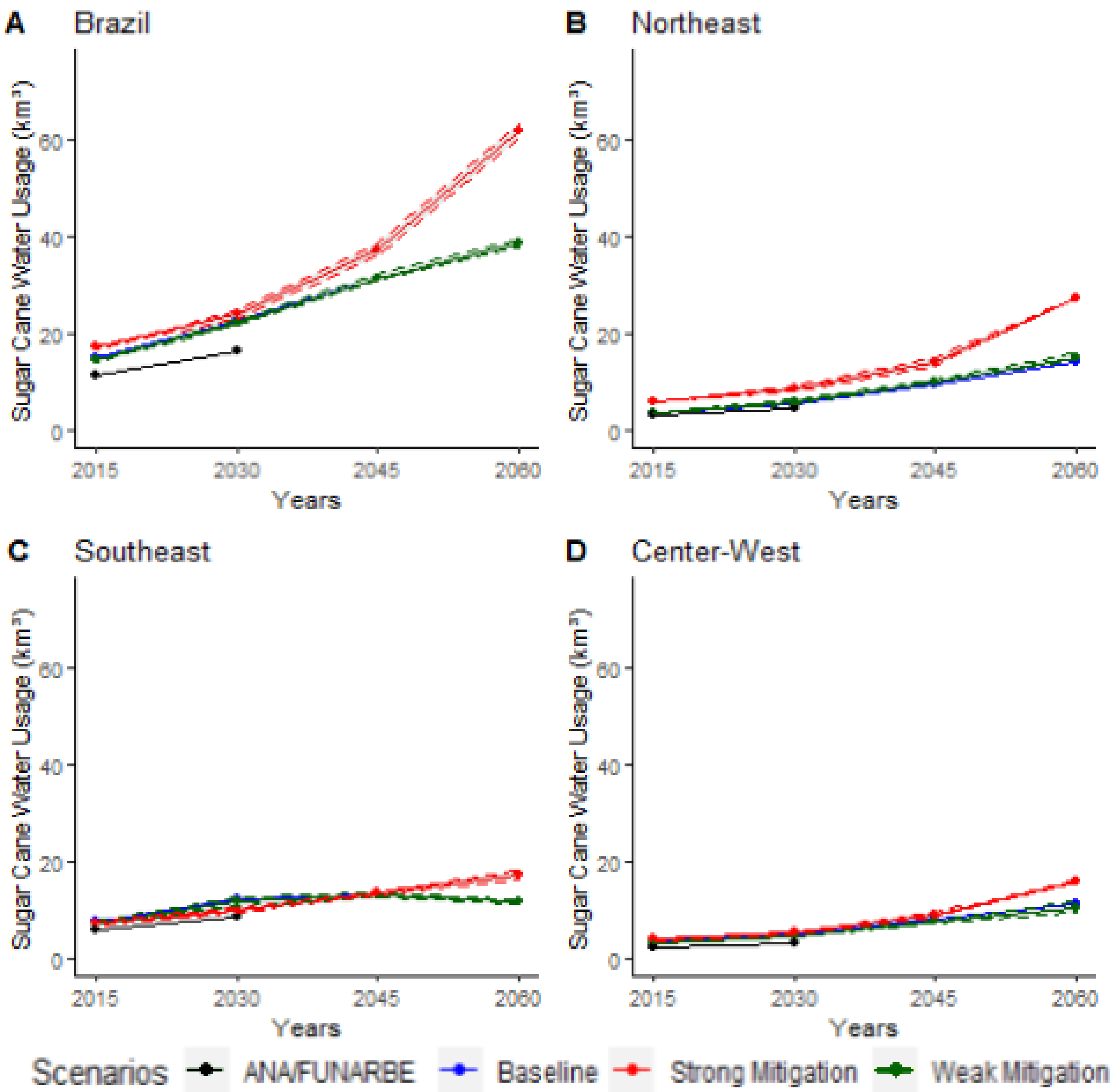


Figure 5.4 Evolution of water used for sugar cane irrigation with uncertainty range derived from possible CO² Fertilization

water use in the Northeast is that the lower water requirement of the crop allows areas with reduced water availability to produce it.

5.3.2 Water price

Water prices increase in Brazil, specially in 2060, mostly led by sugar cane production. Figure 5.5 shows that prices in the Northeast double from 2030 to 2045 and than double again until 2060. The South prices more than double in the last time step mainly because of soybeans and maize (although it also irrigates cane from 2045 forward).

When the scenarios are compared it is visible that, although water prices always increase in the Northeast and South in the long run, this growth is much steeper in the Strong Mitigation scenario.

Again, Strong Mitigation increases water scarcity in Brazilian dry regions because it turns it in an important bioenergy exporter. As water itself is not paid for (only the infrastructure to apply it to the fields) the model uses large amounts of water even in areas where its availability is limited.

CO^2 level also has modest results in terms of water price. Again the Northeast region goes against the national value, showing higher scarcity when there is CO^2 fertilization (even though, as was said, sugarcane demands less water in this case). The same explanation is valid: sugar cane´s lower water demand allows new areas, which cannot produce without CO^2 fertilization, to grow sugar cane, increasing scarcity in the area.

5.3.3 Discussion

Two main results were obtained in this chapter: The large effect of a Strong Mitigation effort on Brazilian water resources; and the small effects of CO^2 fertilization on sugar cane production.

Regarding the former, as the rest of the world strives to reduce carbon emissions, substitution of fossil fuels by renewables encourages the production of biofuel sources in more productive areas. As Brazil is an efficient producer of sugar cane, it becames a major exporter of ethanol needing to expand beyond its traditional sugar cane crop area (and moving even further than in all other scenarios where sugar cane production also increases).

This expantion is much more striking in the Northeast region where warm climate and large areas currently non-productive induce the model to allocate a lot of blue water to cane irrigation.

The second interesting result is, although small, very curious and helps to demonstrate the importance of analising all related factors when a water policy is designed. CO^2 fertilization, by reducing sugarcane water demand, allows the crop to grow in very water scarce areas that were otherwise unproductive.

This crop expansion caused by the lower water demand coefficient increases total water use in the entire region and enhances scarcity in the country's driest area. As comparison, regions with higher water availability such as the southeast save water when CO^2 fertilization is considered.

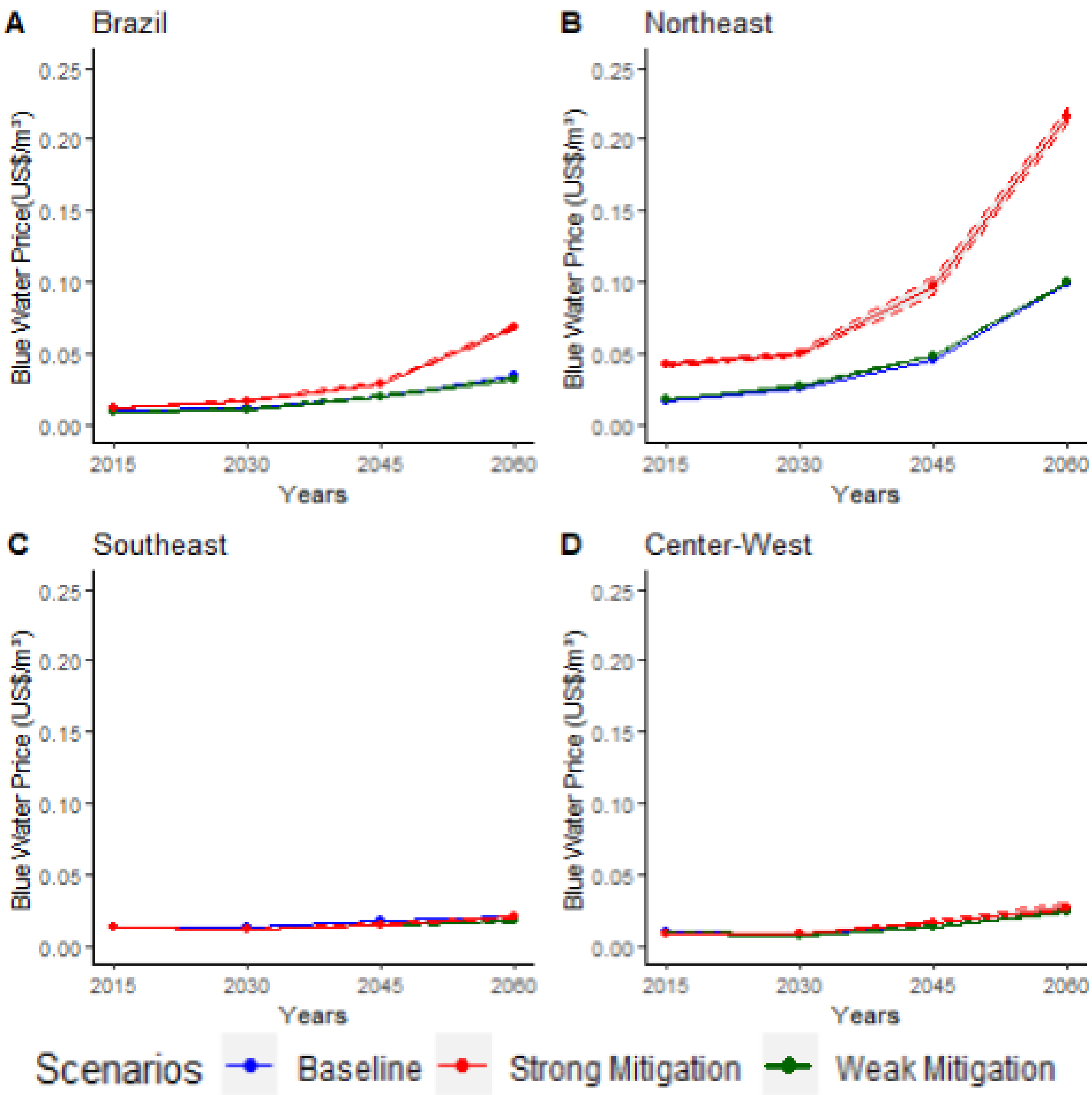


Figure 5.5 Evolution of Water Shadow Price with uncertainty range derived from possible CO² Fertilization

CHAPTER 6

Conclusion

This work aimed to evaluate the impacts on Brazilian water resources of different scenarios related to bioenergy demand, both related to international policies and to different mitigation efforts when climate change is considered. So that both biophysical factors and international trade relations are included in the analysis, the MAgPIE 4 framework was used to create the MAgPIE-Brazil model. This model allowed a more detailed analysis of Brazil without losing the advantages of using a global model, such as trade.

Results for all considered scenarios show that the use of irrigation in sugar cane cultivation in Brazil will escalate until 2060. This movement is, in part, driven by a growing demand for other sugar cane derived products, although ethanol demand has significant effects in the magnitude of this growth. To fulfill this demand, the model replaces large areas which are currently rainfed with irrigated production and turns marginal regions into irrigation equipped areas (mostly in the drier parts of the Northeast and Center West regions) augmenting both area and water use.

When international policies regarding first and second generation biofuels where analised, it is observed that ceasing the production of ethanol from sugar cane has the effect of reducing both water use and its scarcity, as measured by water economic values. This scenario, where only Advanced biofuels are produced from 2040 onwards has positive effects (from the water perspective) even in the Northeast region. On the other hand, the replacement of traditional sugar cane with Cane energy after 2040 only has similar results in the Center-West and Southeast regions. The NE sees its water use unchanged and water shadow price even higher due to the higher price of the fuel.

Looking at the global approach to climate change it is visible the large effect on Brazillian water resources of strong climate change mitigation policies. The effort to reduce fossil fuel consumption increases demand for most renewable sources, including sugar cane. Although water use and economic value hike in all regions, in the Northeast the boost is steeper and, due to its already worrisome water scarcity situation, more important.

Considering these results, it is clear that water availability should be contemplated by policy makers to avoid misallocations and potencially aggravate water scarcity in more sensitive areas. This is even more relevant if strong climate change mitigation measures are adopted, what could lead to a large ethanol demand growth. Studies such as this are important because simplistic measures like forbiding sugar cane irrigation in drier areas might cause other sort of problems (as was discussed, the agricultural sector is very important for developing regions and this kind of intervention could lead to economic problems). Unless Cane energy develops to require less water, incentives to its production alone do not solve the water availability problem either as the Northeast remains a production hub.

The economic value of water, as discussed here, could be a starting point in the valuation of water resources in order to include it in the policy formulation process. If water is well valuated, measures could be taken to reduce externalities of the biofuel production process (turning what is currently a social cost into a private cost) avoiding, at the same time, economic and water scarcity problems.

Through planning and control, it is possible to intervene in the competition between sectors. Public policies which reflect the scarcity values in each region can discourage water-intensive uses in scarcer regions, unless they invest in technologies that reduce their water use. At the same time, the less intensive ones, such as those associated with human supply, become more advantageous.

The development of MAgPIE-Brazil and its use to measure water availability response to global scenarios is an important start but further research could deepen the analysis. Considering grey water issues, as discussed by Castillo et al. (2017), especially in the Northeast, could be an interesting development for this research.

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Appendix A

MAgPIE minimizes a goal function that aggregates all costs calculated in each module of the model. 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):

$$vm.cost.glo = \sum_{n=i} v11.cost.reg_{(i)} \tag{A.1}$$

Regional production cost is in its turn composed of the sum of the costs of different production activities.

$$\begin{aligned} v11.cost.reg_{(i)} = & \sum_{k} vm.cost.prod_{(i,k)} + \sum_{j,land} vm.cost.landcon_{(i,j,land)} + \sum_{j,k} vm.cost.transp_{(i,j,k)} \\ & + vm.tech.cost_{(i)} + vm.nr.inorg.fert.costs_{(i)} + vm.p.fert.costs_{(i)} \\ & + vm.emission.costs_{(i)} + vm.reward.cdr.aff_{(i)} + vm.cost.AEI_{(i)} \\ & + vm.maccs.costs_{(i)} + vm.cost.trade_{(i)} + vm.cost.fore_{(i)} \\ & + vm.cost.processing_{(i)} + vm.costs.overrate.cropdiff_{(i)} \end{aligned} \tag{A.2}$$

Table A.1 briefly describes each of the costs

Among the constraints are the regional demand for food, feed, livestock and materials. Bioenergy demand, both first and second generation, are also a restriction. Specific restrictions on land use are also imposed, such as forest preservation or urban areas.

Table A.1 Description of Costs considered in MAgPIE

Cost	Description
vm.cost.AEI (i)	Irrigation expansion cost
vm.cost.fore (i)	Afforestation cost
vm.cost.landcon (j, land)	Land conversion cost
vm.cost.prod (i, k)	Factor cost
vm.costs.overrate.cropdiff (i)	Penalty for overrated cropland difference
vm.cost.trade (i)	Interregional trade cost
vm.cost.transp (j, k)	Transportation cost
vm.emission.costs (i)	Cost for emission rights for pollutants
vm.maccs.costs (i)	Cost of mitigation of GHG emissions
vm.nr.inorg.fert.costs (i)	Cost of inorganic fertilizers
vm.p.fert.costs (i)	Cost for mineral fertilizers
vm.reward.cdr.aff (i)	Revenues for Carbon captured
vm.cost.processing (i)	Processing cost
vm.tech.cost (i)	Technological change cost

Source: Own elaboration based on the MAgPIE documentation