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# "Current biofuel potential in Argentina and future projections while varying a selection of allocation variables"


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# Preface

With this report I would like to present the work of my thesis, which is part of the Sustainable Development – track: Energy and Resources master program at Utrecht University. Within the years that I followed this program I became increasingly intrigued with controversies that appears to surround many means that aim to promote sustainable development. This is not in any sense strange, since the concept of sustainability implies that continuing past developments is either impossible or unacceptable with the resources that are available. Apart from technological innovation, sustainable solutions may also involve the requirement of unattractive tradeoffs that touch our personal lives. I thereby increasingly realized that whether or not to embrace newly found ecological values in decision making is a matter of value. From the point where the impact of technological development ends, the sustainability of future development thereby rests on the field of politics. This is what I found both the most interesting and difficult about this master program. Since I am not an expert in engineering, physics or chemistry, the contribution that I can make in sustainability issues is to assess the impact of choices, in other words: provide policy makers with the necessary information for them to choose between options. Even though I have my own preferences on what choices should be made and that even when trying to be as objective as possible, my own values are always in some way reflected. Reflected in the choices I make in my research and reflected in the options that I choose to present at the end of my research. That is what I find intriguing.

Biofuel controversy fascinates me due to the obviousness and comparability of its tradeoffs. Whether the interest is food production, eco-system services or biofuel production, all compete for largely the same land area. Considering the extensive land use of the livestock industry and being a vegetarian myself, I became interested in how diet change can not only directly, but also indirectly lead to GHG emission reduction by growing biofuels on former pastures.

After I came to Edward Smeets with this idea, he helped me in starting a research proposal that combined spatially explicit methodology to calculate biofuel potential in Argentina with a scenario approach that moreover involves diet change. During the project I got confused and disappointed with the low availability of spatial data on livestock production. After Edward Smeets left our Department, Andre Faaij took over his role as first supervisor and really helped me a great deal in finding the right track. This included a shift in focus of the research towards assessment of the relative impact of allocation rules, rather than to conceive spatial modeling only as a tool to add precision into the outcome. Although I am very happy with my work and the results of this methodological comparison, I am also a bit disappointed that I could not more extensively model the effect of diet change and potential intensification of the livestock sector due to the mentioned limited availability of spatial livestock data.

It has been a long trajectory. I have particularly enjoyed the modeling and analysis of complex issues. But I have also struggled, with time and with structure. I want to greatly thank Janske and Andre to help me regain focus, to give me the chance to recover from struggles, to help me in recognizing obvious simplicity where all I could see was complexity. Thanks, to my friends and fellow Master students for making studying such a wonderful time for me, especially to Ruud Gelten for also helping me with data gathering and thinking with me when I got stuck. Thanks, to my parents for supporting me and to leave me my own thoughts at the same time. To Pita Verweij, for showing flexibility and kindness in granting me those extra days when I needed them.

This thesis has been the final of an era for me, and I am so happy to have succeeded and passed this stage. Now another awaits.

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# 1 Abstract


Relevance

In the global paradigm of the International Panel on Climate Change's greenhouse gas emission reduction targets, replacement of fossil fuels by biofuels has been identified as one of the measures to realize the targeted emission reduction. However, biofuel production is also potentially controversial. Increasing production puts pressure on the scarce quantities of available arable land. Land that is also important to host food production and ecological services. Biofuel production that interferes with required levels of food production and with existing ecological services (due to land use changes) is considered unsustainable. In order to determine the quantities of biofuel that can be produced sustainably, a spatial approach is needed.

Due to its fuel blending targets since the ratification of a biofuel law in 2006, Argentina seeks to increase its biofuel production. The extent to which biofuels can be produced sustainably is therefore important information for policy makers. Although soybean and switchgrass biofuel potential in Argentina has been previously researched by (Kline et al., 2008) and (van Dam et al., 2009), a spatially explicit approach has been lacking.

Research objective

This study aims to provide insight in how the application of individual and combined static spatial constraints affect the quantity of the potential to produce soybean diesel, switchgrass ethanol and sugarcane ethanol in Argentina, for the current situation and future scenarios. The spatial constraints can concern practical issues that prohibit agricultural management; occupied agricultural areas or environmental protection. This study is not focused on spatially explicit results per se, but rather aims to evaluate the effectiveness of individual spatial allocation rules.

Methodology

First, a geographic potential (covering all Argentinean land) and potential per land use class is calculated to compare the calculated sustainable future potential with theoretic maximum levels. As a conservative approach it is assumed that the spatial constraints leave no area available for sustainable biofuel production in the current situation. In other words, the current potential is assumed to be zero. In future scenarios, shares of cropland and pastures are released by increases in agricultural efficiency or diet change. This area is assumed to be available for potential biofuel production.

While considering the locations and area of environmental protection zones, steep slopes and others as static, projections on the required amount of food production and production efficiency can be used to estimate required area for future food production. However, its location remains unknown. To deal with this, two methods (suitability allocation and homogeneous allocation) are used to spatially allocate food and biofuel crops on cropland area and are compared in their effectiveness of resulting food and biofuel production quantities.

The suitability allocation method uses the suitability maps of FGGD/AEZ to allocate crops on the best suitable locations until province or nation level statistics are met. With 'allocation on the best suitable locations' it is meant that crop A competes with crop B and C for allocation on a particular location. The crop that is most suitable to this location 'wins'. To avoid all areas being allocated one crop, allocation is limited by production area statistics. The effectiveness of suitability on total production quantities is evaluated by a simple method in which crops are evenly allocated on all cropland with a suitability higher than zero for a particular crop (the homogeneous allocation method).

These methods are used to calculate future biofuel potential. In addition to baseline future projections also the effect of diet change and transition into a fully 'landless' livestock sector are reviewed as alternative scenarios. These scenarios involve homogeneous shares of pasture area. Each scenario involves a type of diet, a population level that represents 2015 or 2030, and changes in livestock production efficiency. a crop yield efficiency factor, and a livestock yield efficiency factor. Each parameter has 3 variants. Constructed scenarios are presented in 3 tables, with 1 table assuming no diet change and the other tables representing change to a vegan diet or a moderate diet (50% less animal product consumption in Argentina).

A biofuel pathway analysis is performed to convert the calculated quantities of fresh weight biofuel into a potential of final fuel energy and greenhouse gas emission reduction.

<u>Results</u>

The energy balance of the biofuel pathway results in 6,9 ; 2,1 ; 9,1 GJ/tonne fresh matter for soybean diesel, sugarcane ethanol and switchgrass ethanol respectively. The GHG emission reduction balance results in 52 ; 64 and 65 gram CO2 equivalent per MJ final fuel. Due to the low performance of rainfed sugarcane, this feedstock was not included in future potential calculations.

Comparison of the two used methods has shown that Suitability allocation is slightly more effective than homogeneous allocation with the given input. Suitability allocation is used to calculate all scenarios.

Sensitivity analysis with regard to annual crop yield increase has shown that an increase in yield growth leads to an increase of biofuel potential, but with diminishing returns per unit of increase, once the yield growth rate passes 1,67 % annual growth.

From the geographic potential, the Sugarcane irrigated – ethanol pathway is the most potent (10.457 Mtonnes/year ; 11.521 PJ/year; 734 Mtonnes/year, as fresh matter, energy content and CO2 equivalent emission reduction respectively ). Sugarcane rainfed – ethanol (98 Mtonnes/year ; 105 PJ/year; 7 Mtonnes/year) is the utter least potent in Argentina. The potential of switchgrass ethanol (792 Mtonnes/year ; 6.654 PJ/year; 429 Mtonnes/year) is lower than that of irrigated sugarcane ethanol but does not require controversial irrigation. Because of the preference of rainfed over irrigated biofuel production, switchgrass ethanol is considered a more feasible and future oriented pathway than sugarcane ethanol. The soybean biodiesel potential is 438 Mtonnes/year; 2.438 PJ/year; 127 Mtonnes/year.

Regarding soybean diesel, the performance of final fuel potential is relatively poor, whereas the effective energy production and the GHG emission savings are very poor compared to the other biofuel pathways.

Scenario results of future potential are presented in tables and can be found in the results section of this report. Observations regarding these results are the following.

Future potential in 2015 without any changes in diet and livestock system is 4% of the geographic potential in 2007, but increases by diet and livestock changes.

The final fuel energy of switchgrass potential is 2-3 times higher than that soybean potential.

Including pastures in the potential under baseline conditions leads to 41 – 55 % higher potential levels, depending on the biofuel type and year. Assuming a full transition to landless livestock adds another 463% ; 487% ; 87% ; 124% to the potential of 2015 soybean ; 2015 switchgrass ; 2030 soybean and 2030 switchgrass respectively.

Scenarios involving a moderate diet change under baseline conditions, including pastures, generate 11 times more potential in 2015 and 4 times in 2030. In case of a transition to fully landless livestock, a moderate diet doubles biofuel potential. The same scenario's but then involving a vegan diet change under baseline conditions, including pastures, generate 16-17 times more potential in 2015 and 5 times in 2030. In case of a transition to fully landless livestock, a vegan diet triples biofuel potential.

Conclusion/discussion

One important point that can be made from the results of this study is that although the far most attention and detail has been put in rule based allocation of biofuel on cropland, the resulting quantities are much lower than the more crudely calculated potential that can be withdrawn from pastures in case of a theoretical change in livestock system or diet. More detailed modeling to evaluate the spatial effects of changes in the Argentinean livestock sector is the most essential element lacking in this study and is thus open for further research. Further interpretation of the results can be found in the conclusions and discussion section of this report.

# 2 Introduction

## General

In order to tackle climate change issues, the Intergovernmental Panel on Climate Change identified the replacement of fossil fuels by a more sustainable alternative, as an important tool to reduce greenhouse gas (GHG) emissions. Biofuels may play a key role in the transportation sector, which currently relies for 95% on petroleum based fuels. Globally, this sector accounts for 23% of the GHG emissions (Kahn Ribeiro et al., 2007). Road transport accounts for 74% of these emissions. The IPCC estimates that a share of 10% of the petroleum use in the transport sector can be replaced by biofuels. However, the availability of biomass for the production of biofuels and its effect on the environment and humans, are uncertain. With limited land resources and required conservation or even expansion of existing land use functions e.g. food production and the protection of high biodiversity areas, future increases in biofuel production are potentially unsustainable. Also, the fossil energy use and carbon emissions during the well to factory gate fuel production pathway may introduce controversy if the emissions during the biofuel production pathway nullifies a major part of the mitigated emissions from avoided fossil fuel use.

Global biofuel potential studies such as (Smeets et al., 2007) and (Hoogwijk et al., 2005) estimate that the highest biofuel potential is located in Latin America, sub-Saharan Africa, Russia and the Baltic States. In Latin America, Argentina has a large agricultural industry and is a net exporter of various food commodities as well as animal feed (FAOSTAT 2007), of which the latter primarily concerns soybean production.

Argentina has a large land area of 278 million hectares and stretches long from north to south (3900 km)). Due to the shape and location of the country, the climate concerns four types; warm, temporate, arid and cold. Warm and temporate regions are situated in the north and share borders with Bolivia, Paraguay and Brazil. Especially in the northern warm and moderate regions, the level of agricultural production is high. Argentina has 31 million hectares of cropland, of which 51% is used for soy production. An additional 100 million hectares are pastures (FAOSTAT 2007).

In spite of the developed agriculture, Argentina has only been a marginal supplier on the global biofuel market, with zero ethanol fuel production in 2006 **(USDA 2006)**. Subsequently, the ratification of a blending target for the transportation sector in 2006 (specifically aimed at soybean biodiesel) has been expected to gradually boost soybean biodiesel production. As a result of this policy, the export of soybean diesel in 2007 has been reported at 300.000 tonnes (Hamaide, ), and is expected to reach a level of around 1,1 – 1,2 million tonnes in 2008 (BCR 2008). However, with a high level of agriculture already present, and extensive forests with biodiversity hotspots as surroundings, there is little undefined space to consider for new biofuel production in order to avoid competition with food production. In this study, a decrease in food production per capita and loss of environmental services such as forests and biodiversity hotspots is considered unsustainable. Tradeoffs are an inevitable consequence of changing land use patterns. A sustainable biofuel potential is defined as potential that enables retention of food production per capita and various environmental services. Also, carbon emissions that are related to the biofuel production should be low in order to ensure the effectiveness of the biofuel in reducing GHG emissions.

## Research objective

This study aims to provide insight in how the application of individual and combined static spatial constraints affect the quantity of the potential to produce biofuels in Argentina, for the current situation and future scenarios. The spatial constraints can concern practical issues that prohibit agricultural management, occupied agricultural areas or environmental protection. Biofuel production on these areas is considered unsustainable. Although food production can be conceived as a static constraint in the current situation, changing demand for food and increasing agricultural production efficiency in the future requires reallocation of food and optionally, biofuel crops. Two methods are used to spatially allocate food and biofuel crops and are compared in their effectiveness of resulting food and biofuel production quantities. In addition to baseline future projections also the effect of diet change and transition into a fully 'landless' livestock sector are reviewed as alternative scenarios.

**The main research question is the following:**

"How do spatial constraints and different methods of reallocating food and biofuel crops affect biofuel production quantities in scenarios up to 2030?"

**Sub questions**

1. What is the biofuel potential per type of land area in 2007, while disregarding biodiversity hotspots, high land slopes and areas distant to infrastructure, expressed in fresh matter, energy content and GHG emission reduction?
2. What is the 'sustainable' biofuel potential in 2015 and 2030, considering both baseline and alternative livestock farming scenarios?
3. How is this biofuel potential affected by the choice of methodology on how to allocate food and biofuel crops?

## Spatial Explicitness as a tool to deal with tradeoffs

In order to determine biofuel potential of a country with such diversity in climate and land cover types as Argentina, acknowledgement of spatially explicit constraints enables a more visualized distinction between sustainable and unsustainable potential. A non-spatially explicit estimate of soybean and switchgrass biofuel potential in Argentina has already been made by (Kline et al., 2008) and (van Dam et al., 2009), but a spatially explicit evaluation of biofuel potential has so far not been carried out. The type of spatial constraints that are taken into account in this study include land use functions, slopes, environmental protection areas and distance to infrastructure. Regarding the tension between the production of biofuel feedstock and food, it is considered that although there is demand for both product groups, food production should be given priority. Hence, additional potential should arise from new cultivation areas, or increased efficiency. This includes future prospects in expected growth of food demand due to population growth. The biofuel potential is determined for a selection of fuels and related conversion pathways.

Although current Argentinean policy measures are specifically aimed at biodiesel production from soybean oil, this study aims to explore the potential of 4 systems, involving 3 feedstock types. Three feedstock types and related pathways are selected to represent first and second generation pathways, namely: soybean, sugarcane and switchgrass. Furthermore we have distinguished rain fed and irrigated productivity with regards to sugarcane ethanol production.

## First vs. second generation biofuels

There are 2 main types of biofuel products;

- **First generation** fuels are derived from sugar, starch or oil crops that can also function as food sources. Also, first generation fuels can be produced from food production residues of both plant and animal origin. Some of the food that is produced is wasted, and some of this waste can be converted into biofuel: this is a feedback stream that can contribute to biofuel potential. To account for this, a fraction of food production can be allocated to first generation biofuel production.

- **Second generation** fuels are derived from woody and herbaceous plant parts that are not suitable for food production (lignocellulosic biomass). Although these fuels may be produced from agricultural residues or forestry residues (feedback streams from industrial processes), larger amounts of biofuel can be produced from dedicated crops such as switch grass or dedicated forestry. Fuels derived from dedicated forestry cannot be harvested as regularly as agricultural crops. Although second generation fuels (based on conversion of lignocellulosic biomass) are expected to render significantly higher yields than first generation fuels (Fischer et. al), and are less likely to compete with food crops due to its less stringent soil requirements, these fuel production technologies are still in development and not yet ready for large scale application.

Soybean biodiesel has been selected as first generation fuel because of the already abundant cultivation of soybeans in Argentina. Sugarcane is as a first generation biofuel that is converted into ethanol. It is particularly interesting due to its high productivity and dependence on irrigation. This crop has the second highest production quantities of Argentina, after soybeans. The biofuel potential of from sugarcane feedstock is calculated for irrigated and rain fed conditions to evaluate its dependence on irrigation. Ethanol production from switchgrass represents a second generation pathway and concerns a promising, future orientated type of feedstock. There is no current commercial production of it in Argentina.

Next to taking into account spatially explicit constraints, this study uses scenarios to determine the combined effect of parameter alterations in the parameter assumptions of; food demand through diet changes, population growth and agricultural efficiency. Also intensification of the livestock sector can benefit biofuel potential. The reason for introducing scenarios of alteration in food demand trough diet change is simple. The modern affluent diet contains large proportions of meat, poultry and dairy products which require large amounts of pasture land. Diet change could lower the amount of land that is required for food production. This indicates that diet changes may be an important, but yet controversial tool to make more land available for biofuel production and thereby increase the potential.

# 3 Methodology

## 3.1 Introduction

This research aims to identify the biofuel production potential in Argentina in a spatially explicit way . This potential concerns the current situation but also analyses production potential in future situation. Since the future is uncertain, this is done by the use of scenarios, which involves the use of various parameters.

Calculation of the current potential per land type is made through a static analysis in which the total area of Argentina is narrowed down to a level where only the least controversial areas are still considered for potential biofuel production. Secondly, a comparison of methodologies to allocate biofuels onto the narrowed down area is made.

The current potential per land type is calculated by using calibrated biofuel production maps in overlay with land use classification maps and furthermore a set of constraints that involve biodiversity hotspots, high land slopes and areas distant to infrastructure. The results of this in fresh matter are combined with an energy and GHG balance to calculate the energy content in the final fuel and the gross carbon emission reduction. This potential per land use type is meant to indicate what land types carry the largest biofuel production potential. It is not considered to be 'sustainable' potential.

<u>Conservative approach</u>

It is decided to use a conservative approach in labeling potential as sustainable. To avoid controversial land use change that is moreover characterized by the release of carbon stock, it is assumed that in the current situation all suitable land is 'pre-occupied' by either ecological functions (forests, protected areas) or food production (crops and livestock). Hence the current potential level is assumed to be zero. In future scenarios, efficiency increases of agriculture and diet change can enable a release of pre-occupied land, after which biofuels can be grown.

For this study, there is no essential difference between first and second generation fuels with regard to competition with food production. Next to the potential production quantity of a biofuel or its potential GHG emission reduction, also environmental and economic considerations may prefer the choice for one type of feedstock over another. However, the latter considerations are not analyzed in this study.

<u>A scenario approach</u>

Concerning sustainable future potentials, agricultural area that is required for food production is assumed to grow proportionally to the projected population size (UN). However, a counteracting increase in agricultural efficiency or diet change can release land area for biofuel production without affecting food supply.

<u>Spatial explicitness</u>

Two crop allocation methods are compared to model the release of agricultural land and its effect on the biofuel potential spatially.

<u>Levels of potential</u>

The potential to grow biofuel feedstock is limited by various factors of geographic, climatic and environmental factors. The final production potential is thereby a function of yield performance and a number of land availability constraints. The following levels of potential are distinguished in this study and are used as intermediate results or presented as final result:

- **Geographic potential** : The theoretical upper limit of bioenergy production that is set by the geographic boundaries of Argentina. The theoretical potential excludes bioenergy production from seas, oceans and land outside the boundaries of Argentina. It does include all land and water bodies within Argentina. This is further explained in chapter *3.2.2 Using Globcover*.

- **Land use class potential**: The Geographic potential that is limited by subsequently applying spatial constraints from various spatial databases. These constraints concern: environmental protection areas, global heritage locations, biodiversity hotspots, a terrain slope level of higher than 8% and distance to main roads of more than 100 km. The Globcover land use classification database is used to present potential results per land use type.

- **Future potential**: Adaptations in diet and agricultural efficiency could decrease the required amount of cropland and pastures for food production, and thereby release a part of this land for biofuel production. A scenario analysis evaluates these effects in order to calculate future biofuel potential. Cropland and pasture area is calibrated using "Sistema Integrado de Información Agropecuaria" (SIIA) and FAOSTAT data. Two crop allocation methods are used to 'predict' future distribution of food and biofuel crops and how this affects biofuel potential quantities.

The results of the potential levels are presented as fresh weight of raw feedstock, energy content of the final fuel and reduction of GHG emissions. The fresh weight potential concerns fresh matter of biofuel feedstock in kg/ha that is used as input to subsequent stages of the biofuel production pathway. The potential is also given in energy units (defined as *energy potential*), which is done to address the differences in energy content of the feedstock types. An energy and GHG balance of the production pathways is used to determine the potential of GHG emission reduction and the net. energy potential.

Scenarios are used to assess the impact of variations in population size, agricultural efficiency increases and diet change. Future scenarios of 2015 and 2030 are represented by UN population prospects of these respective years.

Determination of the fresh weight potential is divided in the following main themes: available land and land productivity. The methodology is structured in such a way that firstly the theme of available land is elaborated, signifying the available land per level of potential in separate paragraphs. Secondly, land productivity is elaborated. The product of the two themes is potential of feedstock in fresh weight. Note that this does not yet account for differences in energy density of the feedstock, as well as for energy losses and GHG emissions in the production pathway. The latter is elaborated in chapter 3.6. Energy and carbon emission balance of Biofuel production pathways.

## 3.2 Available land: Constraints

Various data sources are used as constraint areas in order to restrain these areas from biofuel production potential. The remaining area is used to calculate the Geographic potential These constraints are the following.

- Geographic boundaries of Argentina
- Protected areas, biodiversity hotspots and world heritage locations

- High slopes
- Distance to main roads

Subsequently, Globcover land use classification data is used to calculate the Land use class potential.

The results of land area are used in combination with potential yield data to calculate fresh weight potential. The listed constraints above and an elaboration on the use of Globcover are elaborated in the following paragraphs.

### 3.2.1 Geographic boundaries of Argentina

The area of all land and water bodies within the boundaries of Argentina is used in combination with productivity data to determine the Geographic fresh weight potential. It is presented as a reference to how the performance of the current potential with all its constraints relates to the theoretical geographic maximum.

### 3.2.2 Using Globcover

The original regional land use classification system of Globcover (considering the regional dataset of South America) uses a large number of classes. See 8.1 *Land use classification* for details. The number of classes is decreased by merging classes of similar characteristics into a set of group classes (see Appendix: Land use classification). Land use classes from Globcover are grouped into thematic layers and are used in combination with potential productivity data to determine the Land use class potential on any location on the map of Argentina.

It should be noted that *pastures* as a term is not defined by Globcover, in contrast to *cropland* which is readily defined by this spatial database. In order to spatially identify pastures (such as defined by the FAO production yearbook), it has been decided to consult additional, external databases that are specialized to spatially visualize pasture lands.

A dedicated database for pasture land is consulted: Occurrence of pasture and browse (FGGD) from the FAO is a dedicated database for pasture lands, and is shown in Figure 31 of the appendix. This data shows that the highest concentrations of pasture land are situated west of the Pampas area and within the Pampas area. Since it is aimed to use the classes of Globcover, the "Occurrence of pasture and browse (FGGD) database" is not used directly, but to identify pasture lands within the spatial distribution of classes in Globcover. Comparison of FGGD with the Globcover map shows that the spatial distribution of pasture lands are similar to the distribution of shrubland in Globcover. Globcover shrubland is therefore attributed the function of permanent pastures.

As part of the conservative approach, all land use classes (ice covered regions, bare areas, urban areas, water bodies and forests) except for cropland, sparsely vegetated areas and shrublands are by definition assumed not to be able to host sustainable biofuel production. While physical limitations determine the unsuitability of ice covered regions, urban areas, bare areas and water bodies, forests are excluded due to their high carbon stocks and ecological value. Excluding forest areas entirely is considered the most responsible choice from this perspective. Without the criteria of sustainability, forest land would be highly suitable for growing biofuel crops. Cropland and shrubland are assumed to fully host food production in the current situation, but are assumed to release shares of land in the future. The location and quantity of the released area is determined by the two crop allocation methods that are used (3.4 Crop allocation models), and subsequently used to determine future potential. This means that only Sparse vegetation lands remain available in the current situation.

### 3.2.3 Protected areas, biodiversity hotspots and world heritage locations

In order to avoid loss of biodiversity due to land use change it is assumed that lands that are registered as environmental protection zones e.g. natural parks, should be excluded from the potential. To do this, spatial information from the World Database on Protected Areas (WDPA) has been used to determine the spatial extend of these areas. Argentina counts 306 registered terrestrial nationally designated protection areas. These areas also include very small locations that are spatially visualized as point data, whereas the larger areas are visualized as shape data. Since point data cannot be properly visualized on a raster, it is decided to subtract only the larger areas from the geographical potential. Subtracting only natural protection zones is not considered sufficient, as these do not serve the protection of diversity of wildlife species. To account for this, areas that are defined as 'biodiversity hotspots' by WWF are also subtracted from the potential. Finally, areas that are on the UNESCO list of world heritage are excluded.

### 3.2.4 Steep slopes

Lands with steep slopes (so called 'steeplands') are considered unsuitable for bio fuel crop production due to their sensitivity to erosion and difficulty of harvest. Although the approach of the European biofuel potential study of Refuel assumes a 16% slope as a feasible maximum (Fischer et al., 2007) it is decided to use a more conservative assumption of 8% (Wicke et al., 2009) in order to discard steep lands from the potential. Note that the level of feasible slope depends on the type of crop that is grown. However, differentiation in slope levels is not made in this study. The slopes in Argentina have been calculated from the GLOBE elevation database.

### 3.2.5 Distance to main roads

From an economic and practical point of view, it is decided to discard areas far away from infrastructure out of the potential. This implies using a threshold of a maximum allowable distance between the cell centre and the nearest infrastructural element. This actual distance is the shortest straight line to a nearby road. After determining the distance per cell, the output cells with a distance higher than the threshold can be discarded from the potential map. It is assumed that biofuel potential on a location that has a distance of more than 100 km to a main road is unfeasible. In Figure 30 of the appendix it is shown, how the distance to relates to the location in Argentina. As can be seen, the infrastructural network of roads in Argentina covers the country well, with a maximum distance of 90 km to a main road. This is therefore not considered to be a limiting factor.

## 3.3 Potential yield

The yield data sources that have been used to calculate future potentials are slightly different from the data sources that are used to calculate Geographic potential and Land use class potential. These differences are explained per parameter.

There is an imbalance between the information that is available, considering the types of feedstock that have been selected. While for all feedstock types, the spatial distribution and quantity of potential productivity all use potential productivity data of IMAGE (see next paragraph), the possibilities to calibrate this data with empirical productivity data vary greatly. The results will thereby be subject to a varying uncertainty, which should be noted while interpreting them.

### 3.3.1 Application of productivity data

#### *3.3.1.1 Soybeans yield performance*

##### 3.3.1.1.1 Geographic potential and Land use class potential

From the biomass feedstock types that are reviewed in this study, soybeans are already produced on a large scale in Argentina. Because of this, a large amount of data on current soybean yields and area is readily available from statistics of the ministry of agriculture and the FAO. Statistics from the ministry of agriculture are available per province, and are used as a correction factor to the MAPSPAM (see Appendix: 8.4.2.2 MapSPAM spatial production allocation) soy production map. The described data is used to calibrate the soybean yields both spatially and quantitatively. The calibrated MAPSPAM map is then used to spatially and quantitatively correct the IMAGE potential productivity map of soybeans.

##### 3.3.1.1.2 Future potential

The published results of the MapSPAM model concern soybean production area and yield. However the yield data is only given on locations where production area is allocated. Since future potential calculations require reallocation of crops, yield data is also required for locations on which no current area is allocated. Hence, MapSPAM yield maps are not useful. Instead it is decided to use FGGD/AEZ spatial relative suitability datasets of oil crops, calibrated with nation level yield statistics and used in overlay with IMAGE potential soybean productivity data to cover Argentina entirely. Information on why and how relative suitability maps for soy and other crops are used in suitability allocation modeling is elaborated in 3.4.1 Using FGGD/AEZ spatial relative suitability datasets.

#### *3.3.1.2 Sugarcane yield performance*

##### 3.3.1.2.1 Geographic potential and Land use class potential

In the case of sugarcane yields, considerably less reference data is available. Considering the reference data, there are inconsistencies between the data reported by FAOSTAT and the statistics from the ministry of agriculture. The production statistics of the Ministry of Agriculture (6.799.055 tonnes/year) are much lower than that of FAOSTAT (24.400.000 tonnes/year) in 2005. The reported yields from the ministry are comparable to the yield range from the potential productivity database of IMAGE. IMAGE yields vary from 0 in unsuitable areas to 104 thousand tonnes/ha/year in fertile regions while the ministry reports a lowest average yield of 17 thousand tonnes/year in Chaco and a highest average yield of 91 thousand tonnes/year in Salta. For comparison: Brazil, which has the largest sugarcane production has an average productivity of 73,3 tonnes/ha (sugarcanecrops.com). As the average of yield statistics over all provinces is 65.945 tonnes/ha compared to 86.241 tonnes/ha of IMAGE, a correction factor is applied to the IMAGE potential productivity data.

##### 3.3.1.2.2 Future potential

For the reason of poor rainfed performance under irrigated conditions, it is decided to not include sugarcane ethanol in future potential calculations.

#### *3.3.1.3 Switchgrass yield performance*

##### 3.3.1.3.1 Geographic potential and Land use class potential

Concerning the performance of switchgrass there are no statistics available or other empirical data that indicate yields of switchgrass as a biofuel crop in Argentina. Some experimental fields have been grown, and also, some empirical data is available of switchgrass from around 1970 in North America, where it has been used as a fodder crop. Reported yields of below 4 tonnes/ha back then were common. (Parrish & Fike, 2005). Recent studies regarding switchgrass as a biofuel crop have shown extremely varying results, from 0 tonnes/ha due to poor cultivation practices (Parrish & Fike, 2005) to a top 36.7 tonnes/ha at an experiment in Oklahoma, USA (Thomason et al., 2005). The variation in yield can have numerous causes that concern climate, and agricultural practices. (Parrish & Fike, 2005) state that considering these results, it should be possible to generate yields of over 15 tonnes/ha in regions that have more than 700 mm of rainfall per year. Regarding Argentina, more than half of the country's surface (particularly south and west of the Pampas region) does not meet this demand, and is expected to generate much lower yields.

INTA, whose expertise regards agriculture in Argentina, reports switchgrass yields with a range between 5 and 12 tonnes/ha. Surrounded by the uncertainty, limited empirical data and a high variation in experimental yield results, it has been decided to rely on the national expertise of INTA rather than using (a combination of) foreign experimental results. The range of 5 – 12 tonnes/ha is used to calibrate IMAGE productivity data of "precipitation based grasses", which is used as a proxy for the spatial variation of switchgrass performance. These assumptions cause the uncertainty regarding switchgrass biofuel potential to be much higher than for biofuels based on soybeans and sugarcane.

##### 3.3.1.3.2 Future potential

An overlay of the FGGD/AEZ spatial relative suitability 'fibres' dataset and IMAGE "precipitation based grasses" is used in calibration with a 5 – 12 tonnes/ha range.

## 3.4 Crop allocation models

The previous paragraphs have stated how various spatial constraints are identified to determine where no biofuels should be grown in any case. In the current scenario also the remaining Globcover cropland and pasture area (shrubland) are unavailable as these are considered to be in use. Area of cropland and pasture is expected to be released for biofuel production, but the previously described constraints are not capable of predicting on which geographic locations of cropland, land is released and on how quantities of released land vary spatially. An important pre-condition to do this is that it has to be 'known' how crop distribution behaves in order to assess how a decrease in required area for food production can cause a spatial redistribution of food crops. Consequently, biofuels may fill the gaps that emerge. Complex models have been built in the past to simulate crop distribution, of which MapSPAM is a recent example.

MapSPAM uses a 'cross-entropy' method to determine crop distribution patterns, using suitability of surface, cropping intensity, prices and population factors. Also it uses spatial constraints and local production statistics to calibrate distribution levels. However it should be noted that this model advanced as it is, uses current situation data and has not been built to predict future crop distribution patterns.

Building a similar model to predict future crop distribution patterns is considered too complex with regard to the timeframe of this study. Instead it has been decided to develop and apply different simplified methods to allocate crops.

The rationale of using different methods is to evaluate effect of different allocation rules on distribution and production results. Two methods have been built to assess the effect of using crop suitability criteria (one of the MapSPAM components). The first model uses the suitability maps of FGGD/AEZ to allocate crops on the best suitable locations until province or nation level statistics are met. With 'allocation on the best suitable locations' it is meant that crop A competes with crop B and C for allocation on a particular location. The crop that is most suitable to this location 'wins'. To avoid all areas being allocated one crop, allocation is limited by production area statistics. The effectiveness of suitability on total production quantities is evaluated by a simple method in which crops are evenly allocated on all cropland with a suitability higher than zero for a particular crop (the homogeneous allocation method).

### 3.4.1 Using FGGD/AEZ spatial relative suitability datasets

It was initially aimed to use crop specific spatial suitability datasets. However, IIASA's Global Agricultural Zones project has released data of only a limited number of crop groups via FAO's FGGD portal and the GAEZ website, representing rainfed cereals, fibres, pulses, rice, cotton and oil crops as relevant suitability data sources for Argentina. The 21 crops that Argentina counted in 2007 are aggregated into crop groups as shown in

| assigned crop group | crop type |
|---|---|
| **cereals** | oats |
| | barley |
| | feed barley |
| | rye |
| | corn |
| | millet |
| | wheat |
| | durum |
| **oil crops** | safflower |
| | rape seed |
| | sunflower |
| | peanut |
| | soya bean |
| | Jojoba |
| **fibres** | flax |
| | sorghum |
| **pulses** | birdseed |
| | dry beans |
| **Cotton** | Cotton |
| **Rice** | Rice |

Table 1.

| assigned crop group | crop type |
|---|---|
| **cereals** | oats |
| | barley |
| | feed barley |
| | rye |
| | corn |
| | millet |
| | wheat |
| | durum |

| | |
|---|---|
| **oil crops** | safflower |
| | rape seed |
| | sunflower |
| | peanut |
| | soya bean |
| | Jojoba |
| **fibres** | flax |
| | sorghum |
| **pulses** | birdseed |
| | dry beans |
| **Cotton** | Cotton |
| **Rice** | Rice |

Table 1: Aggregation of crops in suitability groups: the crop types are those harvested in Argentina in 2007 according to SIIA (Argentinean Ministry of Agriculture) data. The crop groups are selected by availability of spatial FGGD/AEZ datasets.

Group yield datasets are created by setting the highest suitability of the FGGD/AEZ datasets (a value of 10.000) equal to the maximum yield of the crop group. The area share per crop determines the weight of the crop yield in the aggregated yield value. The maximum yield of the crop group is determined by calibrating the data with the allocated crop area maps of the first "suitability allocation model" run and national level production statistics.

For soybeans and switchgrass as a feedstock for biofuels, dedicated yield maps have been created . Soybean yield is determined by the FGGD oil crops map and nation level soybean statistics. Since  the FGGD data only covers the agricultural areas in Argentina, the yield data is used in overlay with IMAGE potential productivity data to cover Argentina entirely. In case of switchgrass, an overlay of the FGGD spatial relative suitability 'fibres' dataset and IMAGE "precipitation based grasses" is used in calibration with a 5 – 12 tonnes/ha range. Future scenarios apply growth factors to the yield data.

### 3.4.2 Suitability allocation model

The suitability allocation model uses dynamically repeating cycles of conservative allocation steps until all crops are allocated over available cropland, using Globcover cropland area and crop area statistics ("Sistema Integrado de Información Agropecuaria" (SIIA) and FAOSTAT). This includes biofuels in future simulations. 'Conservative' in the former sentence refers to the continuous feedback between between required area and the quantity of land that is allocated to a specific crop per cycle. Crops are thereby allocated to best possible locations, but no more than required to meet statistical area levels. Allocation occurs per zone of suitability (cells that have equal suitability). Cells on which more than one crop have the same suitability receive a shared allocation.  Since current real crop production is assumed to occur on best suitable locations, the results of this model are used as a reference. Since the homogeneous allocation method (next paragraph) uses yield maps that are calibrated with the results of suitability based allocation,  this model is executed first in time. The model is visualized in Figure 1.

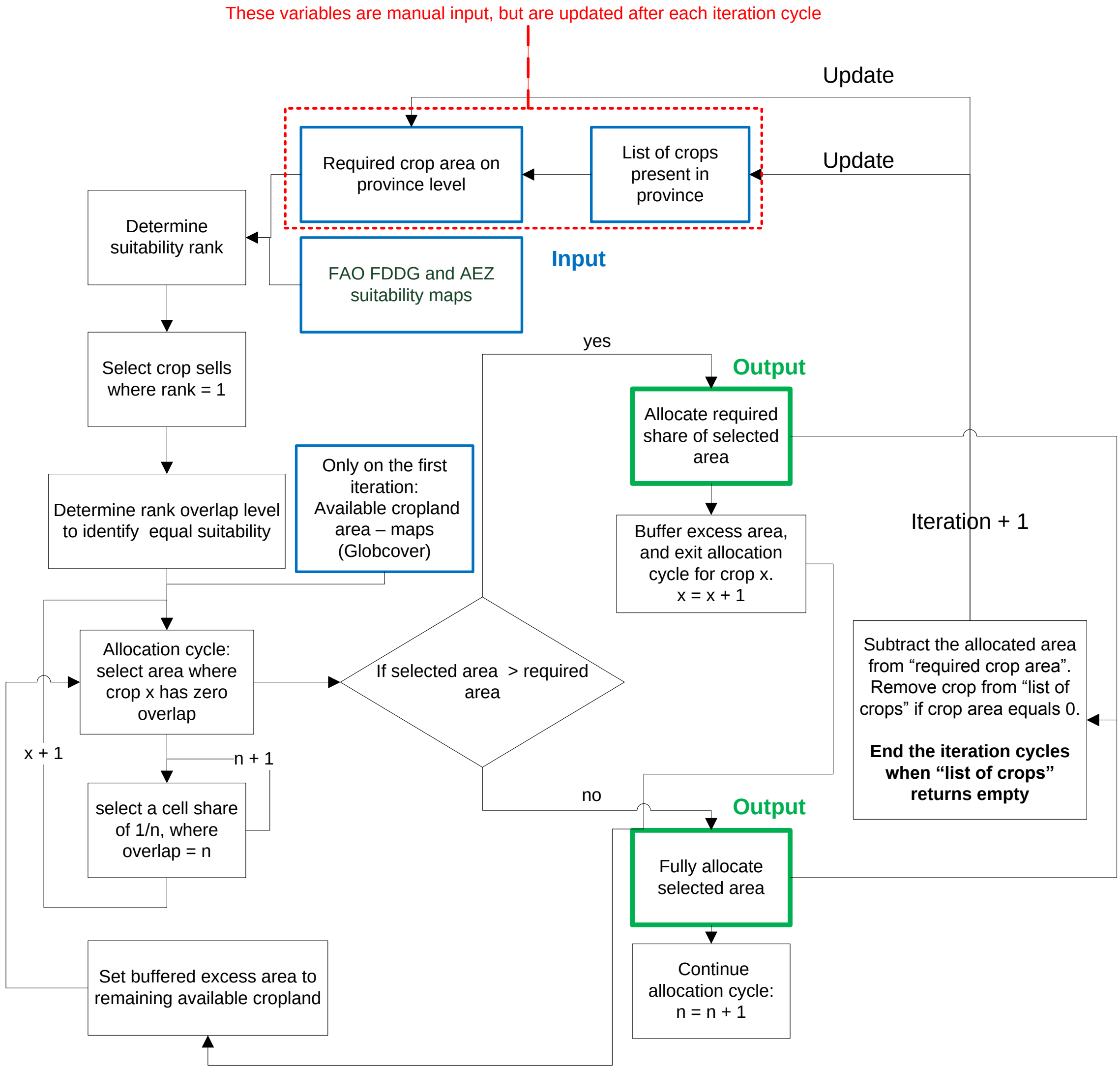


**Figure 1: the suitability allocation model – the model calculates physical area in hectares per cell and generates maps for all crop groups.**

Firstly the model is run for the current situation, with only the total crop area of 2007 allocated, matching province level area statistics. There is no allocation of biofuels. This crop distribution is used as a reference. Yield data is calibrated with this distribution to match province level production statistics.

Increases of future crop yields are translated into a corresponding decrease in required area for regular crops, through which area is released for biofuel production. Updated quantities of regular crops and additional biofuel crops are entered into the model to allocate future biofuels, again using fixed province level area quantities. The allocated area is used in combination with yield data to calculate future potential production levels. This is done in 4 series (involving soybean, switchgrass for 2015 and 2030)  separately for 16 provinces after which the data is merged. Regarding the province of Buenos Aires, the model is run a series of 14 times to determine the effect of increases in crop yield. Unfortunately this procedure could not be performed for all provinces due to time limitation.

Subsequently, the model is run using nation level instead of province level area quantities. Thereby allocation quantities are not bound to province boundaries. This is done in 16 series, involving 8 values of annual yield growth for switchgrass and soy to calculate production levels in 2030. The different values of yield growth aim to spatially visualize allocation displacement and change in potential production quantity through yield growth variation. Ranges of variation are elaborated in 3.7.3 Agricultural efficiency.

Regarding the provinces of La Pampa and San Luis, manual allocation of crops has been performed due to inconsistencies between suitability datasets and the data used to indicate cropland area. In these provinces, the suitability data does not cover all cropland. Manual allocation refers to even crop distribution over cropland.

### 3.4.3 Homogeneous allocation method

In this method, crops are allocated homogeneously over Globcover cropland area and the FGGD/GAEZ suitability maps (not where suitability maps indicated that the suitability for that location is 0). The results of this model are compared with the suitability model by allocating until statistical required areas are reached and subsequently multiply that allocated area with yield maps. The yield maps are calibrated to match production statistics while being multiplied with the allocated area maps of the suitability allocation model. A difference in the calculated production levels illustrates the relative effectiveness of both models. With the homogeneous allocation method being far simpler than suitability based allocation, the former is expected to yield lower production results, and thereby also release less area for biofuels in future situations.

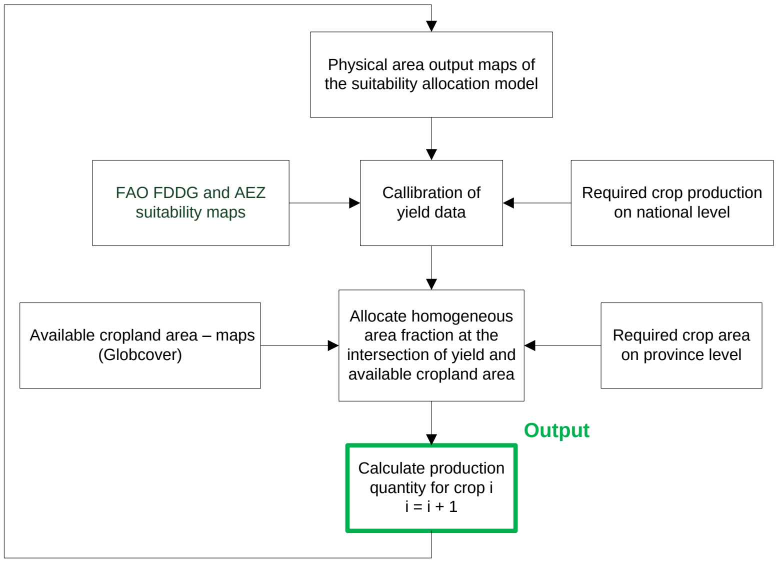


**Figure 2: Homogeneous allocation method - the model calculates physical area in hectares per cell and generates maps for all crop groups.**

## 3.5 Fresh weight potential

Fresh weight potential is the product of area and calibrated yield data. In the cases of Geographic potential and Land use class potential this potential covers all land use classes of Globcover. The results of this are not presented as sustainable potential but aim to give an indication of al potential in Argentina. On cropland area, future potential is calculated from the product of allocated biofuel production area (using the two allocation models) and calibrated yield data. The assumption used for allocation on cropland and pastures are elaborated in 3.7 Scenarios of biofuel production.

## 3.6 Energy and carbon emission balance of Biofuel production pathways

The energy balance and GHG emission balance of the selected biofuel pathways is determined to enable the calculation of the Energy potential and GHG emission reduction potential. Regarding the latter potential, the emissions are compared to fossil fuels by subtracting emissions for avoided fossil fuel combustion. The supply pathways of the selected biofuel feedstock types starts at the cultivation of the feedstock, including several input quantities of energy and chemicals and ends at the feedstock-fuel conversion plant (well to factory gate). Overseas shipping and distribution to the final market is not reviewed, as this study aims to determine (fossil) energy inputs and carbon emissions from a neutral perspective towards the market.

### 3.6.1 Data sources

The energy balance and GHG emission balance during the various stages of biofuel production have previously been researched by JRC (Joint Research Center), in corporation with EUCAR and CONCAWE as part of the "Well to Wheels" program. This program reviews biofuel pathways from a European perspective for many types of feedstock and final fuels (Joint Research Center - European commission, 2007). Input values and results of this study have been used as the main source for calculations regarding the production pathway energy input quantities and carbon emissions in this study. Soybean biodiesel and Sugarcane ethanol pathways are reviewed from cultivation to the final combustion of the fuel in a European car. In this study however, the biofuel production chain is evaluated from cultivation of the feedstock to the manufacturing of the final fuel within Argentina (well to factory gate). Transport outside of Argentina has not been included. Since the JRC study assumes that soybean and sugarcane are grown in Brazil, other transport distances have been used to apply the data on Argentinean biofuel production. These adaptations of input are adopted from INTA (Muzio et al., 2008), who have researched the applicability of JRC soy biodiesel pathway data on Argentina., and mainly concern the transport distance and agricultural input.

### 3.6.2 Application of data

During various stages, energy content of the feedstock is lost, or fossil inputs are required. The lost feedstock represents the fraction from the feedstock energy itself that is lost. The fossil fuel input represents the use of diesel in cultivation, harvest, and transport, but also other fossil input, such as fertilizers, herbicides, pesticides and other fossil non-fuels. Also, all carbon emissions that arise from any fossil inputs are weighed in a balance of greenhouse gas emissions. As a rule of thumb, the input data of energy and GHG emissions of the production pathways have been adopted from the results of the JRC well to wheel program. However, with regard to transport, the data has been adapted to correct for distances in Argentina. Due to the absence of switchgrass ethanol in the review of the JRC program, the pathway of wheat straw ethanol has been used as a proxy for the switchgrass ethanol pathway with regard to transport, energy inputs of fuel conversion and its related GHG emissions. With regard to cultivation of switchgrass and the feedstock conversion efficiency, other data sources have been used (see *3.8 Data Input*). Also, a distinction is made between external energy input and feedstock conversion losses. The assumptions of the energy and GHG emission balance can be found in Table 8 and Table 9 of the chapter Data Input. A more elaborate description of the pathway processes can be found in the Appendix 8.4.3 *Background of biofuel pathways*.

None of the biofuel pathways produces biofuel as a single output. Sugarcane ethanol production involves a waste product that can be used as a replacement for heavy fuel oil. For this, a carbon credit is attributed. Also quantities of waste heat are produced. For this, primary energy and carbon credits are awarded. In case of Switchgrass ethanol, energy and carbon credits are attributed for electricity generation during fuel conversion. Regarding soybean diesel a large fraction of the feedstock is not involved in the fuel conversion processes, as it is directly used to produce animal feed. It is chosen to allocate the energy input and carbon emissions during harvest, bean transport and oil extraction by mass fraction of the oil content of soybeans. Thereby, feedstock used for animal feed production is not counted as feedstock loss. Due to this allocation no attribution of credits is required.

## 3.7 Scenarios of biofuel production

### 3.7.1 Introduction

This chapter describes the scenarios that are used to evaluate the effect of specific sets of variable changes.

The main considered variables are population growth, diet and technological development (agricultural efficiency). Demand can only be met up to the maximum carrying capacity of the land, in this case Argentina. When taking a closer look the various variables, it can be observed that many of the 'variables' are highly inflexible. Population growth can hardly be controlled, demand of nutritional demand per capita remains more or less constant, and the carrying capacity of the land is fixed. However, other variables may be more flexible: the demand for livestock products could be decreased to satisfy the greater biofuel demand. Alternatively, increases in the performance of agriculture could satisfy increasing biofuel demand without a tradeoff.

How the mentioned variables are defined is elaborated in the paragraph of "Variable considerations". Subsequently in paragraph "selection of scenarios" it is presented how the variables are combined in a preset of scenarios.

### 3.7.2 Population growth

Although the change of many variables in the future remains subject to speculation, there is general consensus on the notion that the population of Argentina will grow. This population growth will put more pressure on land use, and since constraints limit land availability it is not possible to retain consumption levels while at the same time protect ecosystem services and also produce large amounts of biofuels without major increases in agricultural efficiency.

Population growth is assumed to have a fixed relation with time. Projections of population growth have been adopted from the United Nations, and involve involving a 'low', 'medium', and 'high' scenario. It is decided to use the medium projection of 2007, 2015 and 2030 (Table 2).

| **2007** | **39.356.383** |
|---|---|
| **2015** | 42.548.000 |
| **2030** | 47.255.000 |

**Table 2: Projected population size. Source: UN - World Population Prospects: The 2008 Revision Population Database**

### 3.7.3 Agricultural efficiency

Historically, the required amount of food production increase has been based on 3 components: expansion of the cultivation area, cropping intensity (also through irrigation) and yield increase. The latter has accounted for approximately 55% of the production increase in Latin America between 1961 and 1999, while land expansion and cropping intensity accounted for 46% and -1% respectively. This is partly a result of increasingly applied irrigation and fertilizer. (Coulter, 2003) Historically, yield increases have been strongly correlated with fertilizer input. Although the previous rise in yield has been linearly related to fertilizer application, diminishing returns are expected for further increased fertilizer application in the future (Harris, 1996) . Hence, yield increases are expected to be lower in the future. Yield increase is projected to account for 46% of the production increase in Latin America between 1999 and 2030, while land expansion and cropping intensity account for 33% and 21% respectively. The expected annual production growth for this period in Latin America and the Caribbean is 1,7%, of which 67% is attributed to increased production efficiency (i.e. cropping intensity and yield increase)(Coulter, 2003). The projected production increase by efficiency gains is thereby approximately 12% in 2015 and 37% in 2030.

#### *3.7.3.1 History of crop yield development*

Production statistics of soybean cultivation in Argentina are available from 1970 onwards, regarding harvested area, physical area and yield. In Figure 3, the historic yield development of soybean cultivation per province is visualized. Although all provinces show a long term historic yield increase, the variation in time is high, with large decreases in yield being almost as frequent as the increases. The underlying cause of yield decrease cannot be derived from this data. Possible explanation may be bad weather, diseases and pests, but also degradation of the soil. Due to the numerous sudden large yield changes, yield analysis over a short period can very easily lead to wrong conclusions about the occurring trend.

There are large differences between the individual provinces, with Cordoba reaching an average of around 300% in the last 10 years whereas Corrientes and La Pampa only benefit an average yield gain of around 60% in the same period.

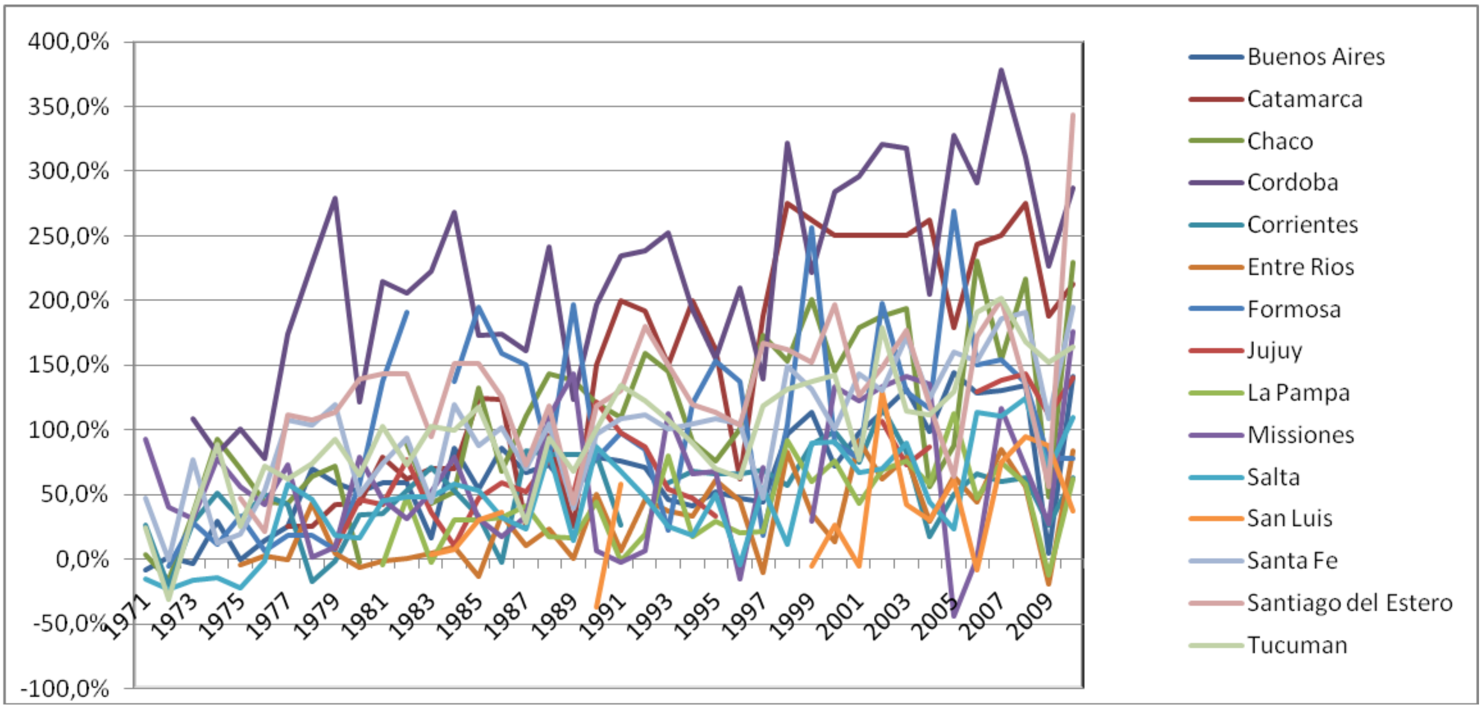


**Figure 3  Soy yield increase in comparison to 1970, per province (SIIA yield statistics per province)**

In Figure 4 the average soybean yield development of all provinces is shown. Trendlines have been added to illustrate that the historic yield development could resemble either logistic, exponential or linear growth, although linear growth has the strongest correlation.  Evaluation of the trend in yield increase in either the entire historic timeline or parts of it (if changes in trend can be observed) can be used as a tool to predict the future development of yield increase. For a example logistic growth trend would imply that soybean yield improvements are projected to level off.

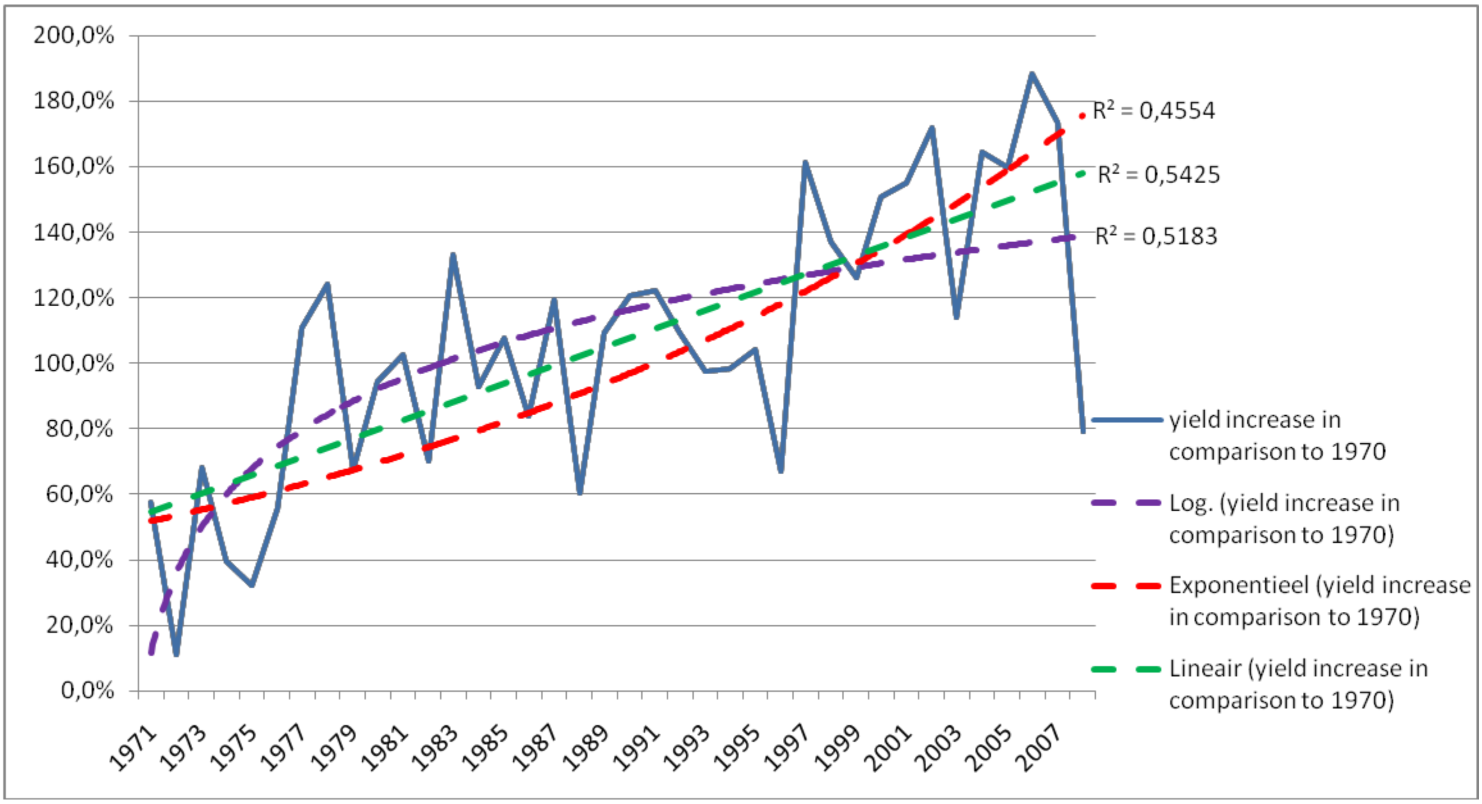


**Figure 4: Average historic soy yield development – country level (SIIA yield statistics)**

Soybean production accounts for a share of over 51,4% of cropland in Argentina. In order to estimate how much area of cropland can become available in the future due to efficiency improvements, yield development of other crops are also reviewed as an aggregated average. From calculations, all crops combined have shown a weighted average annual yield increase (while accounting for differences in land area share) of 3,45% from 1970 to 2009 and 3,1% in the period between 1990 and 2009. Extrapolation of such a trend would render yield increases of over 100% in 2030, compared to 2007. As there are limits in the capacity of the environment, such large margin for efficiency improvement is considered unfeasible. A way to determine a feasible efficiency growth path is to individually compare crop yields with their respective geographically constraint theoretical maximum, such as defined by IMAGE potential productivity data. An aggregated more realistic yield growth projection could thereby be made. However due to time limitation in this study it has been decided not to do this. Instead, the focus is shifted from approaching realistic yield levels towards a review of the effect of yield variation on biofuel potential. As a conservative approach , an annual rate of 1,67% (approximately half the historic yield) is assumed for calculation of the province level statistics – suitability allocation model results in 2015 and 2030. The same assumption is used for calculation of the homogeneous allocation method results.

Regarding the calculations of the province level suitability allocation province of Buenos Aires, 4 values in a range between 1 and 2 % are used to review parameter sensitivity. Due to a lack of available calculation time, parameter variation is only performed for one province: Buenos Aires. The choice for Buenos Aires is due to the fact that it has the largest agricultural area of al provinces. The parameter assumptions and their respective effectiveness in the years 2015 and 2030 are shown in Table 3.

| crop efficiency increase | | 1,00% | 1,33% | 1,67% | 2,00% |
|---|---|---|---|---|---|
| | **2015** | 8,3% | 11,1% | 14,1% | 17,2% |
| | **2030** | 25,7% | 35,5% | 46,3% | 57,7% |

**Table 3 Yield growth assumptions for parameter variation, using the suitability allocation model for the province of Buenos Aires.**

Since there is also a counteracting growth in demand that arises from growing population, actual increase in land availability are lower. A correction for this gives the assumed increases in land availability, as shown in Table 4.

| efficiency increase minus pop growth | | s1 | s2 | s3 | s4 |
|---|---|---|---|---|---|
| | **2007** | 0 | 0 | 0 | 0 |
| | **2015** | 0,2% | 3,0% | 6,0% | 9,1% |
| | **2030** | 5,6% | 15,4% | 26,2% | 37,6% |

**Table 4 Net yield growth assumptions for parameter variation, using the suitability allocation model for the province of Buenos Aires.**

Regarding the nation level allocation runs it is decided to use 8 yield growth values in a range from 1 to 3,33% in 2030 (Table 5). It use chosen to use a larger range than the one used for Buenos Aires in order to estimate the impact of optimistic continuation of past yield trends. With limited time resources it has been preferred to use 8 variations in yield growth for 2030 over using 4 variations for 2015 and 2030.

| annual yield growth | net yield growth in 2030 |
|---|---|
| **1,00%** | 5,6% |
| **1,33%** | 15,5% |
| **1,67%** | 26,2% |
| **2,00%** | 37,6% |
| **2,33%** | 49,9% |
| **2,67%** | 63,1% |
| **3,00%** | 77,3% |
| **3,33%** | 92,5% |

**Table 5: Net yield growth assumptions for parameter variation, using the suitability allocation model on a nation level.**

### 3.7.4 Implications of diet change

This variable provides opportunities. It may save significant amounts of land but also interferes with personal choices of the consumers. This paragraph elaborates on the facets of diet change influence on land requirement in 3 parts. Firstly it is elaborated how the influence of trade is accounted for. The second and third part elaborate on the inefficiency of lacto-ovo-vegetarianism and possible alternatives respectively.

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#### *3.7.4.1 Land requirement effect of trade*

The required amount of land for food production is not only determined by Argentinean demand, but also by import and export. The Argentinean trade balance features a net export of various crops, which predominantly consists of wheat, maize and oil crops e.g. soybeans. Argentina is also a large net exporter of milk, and to a lesser extent also of meat. In this study, export is assumed to remain constant. This means that diet changes of consumers from countries that import Argentinean products are not taken into account. Thereby, exports are assumed to remain constant.

Diet change is assumed not to affect the availability of cropland. Pasture land is assumed to be released for biofuel production by change to a vegan diet, except for the share that is required for export of livestock products. The share of pastures that are required for export is determined by comparing the FAO statistics of production with that of export, regarding the most abundantly produced livestock products in 2007. Product specific land use footprint indicators are used to account for differences in land use between products (Gerbens-Leenes et al., 2002). From the input data (see Table 11 of *3.8 Data Input*), the share of pasture land that is reserved for export is calculated at 12,4%.

#### *3.7.4.2 Alternative types of diet change*

The livestock industry has been evolved to be as efficient as possible, utilizing all the possible products that animals can provide.  Lacto-ovo-vegetarianism on a large scale converts many of the now usable products into waste streams, thereby decreasing its efficiency. Considering this, we conceive a massively applied lacto-ovo vegetarian diet  as unrealistic. As bending the system appears to be very inefficient, a much more efficient solution would be to completely remove the system by eliminating the consumption of all animal products, i.e. application of a large scale vegan diet. In this case, all current pasture would become available for other crops. A more moderate and realistic diet change would be to proportionally decrease the consumption of all livestock products.

It  is decided to select two scenarios of diet change: a massively applied vegan diet, leaving only livestock are for export in use or a moderate diet (50% decrease in livestock consumption in Argentina). The reference is no diet change. Diet change scenarios involve releasing a proportional share of all pastures (a quantity of 99.850.000 hectares, projected over Globcover cropland – FAOSTAT), minus export of 12,4%  (FAO food balance sheets).

### 3.7.5 Livestock efficiency

Although diet change may be an important tool in increasing land availability for biofuels, it is not in line with UN projections and thereby the results of such an assumption form a highly theoretical construct. It has therefore been decided to  evaluate the effect of a land saving phenomenon that does not depend on behavioral change: the transition from pastoral to landless livestock farming. Under baseline conditions, some of this transition (saving 8,4% of land) is expected to take place until 2030 (Bouwman 2005), while a theoretical full transition would save 28% of land. Using these numbers, the quantities of pasture area that are assumed to become available are shown in Table 6

| | |
|---|---|
| **2007 area (reference)** | **99.850.000** |
| **2015 baseline** | 1.927.537 |
| **2030 baseline** | 5.541.669 |
| **maximum intensification** | 28.259.434 |

**Table 6: The reference pasture area, and the amount of pasture area that is expected to be set free under baseline conditions and under a scenario in which all pastoral livestock farming is converted to a landless system (hectares).**

### 3.7.6 Selected scenarios

Each scenario involves a type of diet, a population level that represents 2015 or 2030, and changes in livestock production efficiency. a crop yield efficiency factor, and a livestock yield efficiency factor. Each parameter has 3 variants.

Constructed scenarios are presented in 3 tables, with 1 table assuming no diet change and the other tables representing change to a vegan diet or a moderate diet (50% less animal product consumption in Argentina). All tables combined contain a total of 60 values.

- baseline, excluding pastures
- baseline, including pastures
- baseline, including pastures + irrigation
- landless livestock, no irrigation applied
- landless livestock, irrigated

## 3.8 Data Input

| category | Parameter | Data source | data type |
|---|---|---|---|
| | | | |
| **Spatial constraints** | spatial land use classification data | Globcover | GIS raster data |
| | protected areas, world heritage locations | World database on protected areas | GIS shape data |
| | biodiversity hotspots | Conservation International | GIS shape data |
| | calculation of slopes | GLOBE elevation data | GIS raster data |
| | infrastructure - main roads | Digital chart of the world | GIS polygon data |
| | identifying pastures | Occurence of pastures and browse (FGGD) | GIS raster data |
| | In-use pastures | FAOSTAT - permanent pastures and meadows 2007 | statistics - area |
| | In-use cropland | Argentinean Ministry of Agriculture | statistics - harvested area |
| **relative crop productivity** | rice | GAEZ - plates - Suitability for rain-fed and irrigated rice (high inputs) | GIS raster data |
| | cotton | GAEZ - plates - Suitability for rain-fed and irrigated cotton (high inputs) | GIS raster data |
| | fibres, oil crops, pulses, cereals | FGGD - Land productivity potential (FGGD 6.3 ; 6.10; 6.16; 6.22 ) | GIS raster data |
| **potential yields** | potential productivity of soybeans - rainfed | IMAGE potential productivity database - soybeans rainfed | GIS raster data |
| | soybean production - harvested area callibration | MapSPAM 3.2 - soybean harvested area total | GIS raster data |
| | soybean production - yield | MapSPAM 3.2- soybean yield total | GIS raster data |
| | potential productivity of sugarcane - rainfed | IMAGE potential productivity database - sugarcane rainfed | GIS raster data |
| | potential productivity of sugarcane -irrigated | IMAGE potential productivity database - sugarcane irrigated | GIS raster data |
| | potential productivity of switchgrass - rainfed | IMAGE potential productivity database - precipitation based grasses (proxy) | GIS raster data |
| | potential productivity of switchgrass - callibration | INTA | range of switchgrass yield |

| | | | |
|---|---|---|---|
| **2007 crop area and yields** | oats, barley, fee barley, rye, maize, millet, wheat, durum, safflower, rape seed, sunflower, peanut, soy bean, jojoba, flax, sorghum, birdseed, dry beans, cotton, rice | Sistema Integrado de Información Agropecuaria (SIIA) | statistics – physical area and yield |

**Table 7: Input data (datasets) of Fresh weight potential.**

| Category | Parameter | Value | unit | Reference |
|---|---|---|---|---|
| **cultivation energy** | soybean cultivation | 0,28 | external energy input (MJ/MJ final fuel) | (Joint Research Center - European commission, 2008b) |
| | soybean oil mill | 0,35 | external energy input (MJ/MJ final fuel) | (Joint Research Center - European commission, 2008a) – SYFA + WTET (steam generation) pathway; GEMIS |
| | sugarcane | 0,06 | external energy input (MJ/MJ final fuel) | (Joint Research Center - European commission, 2008b) |
| | switchgrass | 0,13 | external energy input (MJ/MJ final fuel) | (Smeets et al., 2009); (Joint Research Center - European commission, 2008a) – STET pathway; GEMIS |
| | | | | |
| **transport energy** | sugarcane and switchgrass ethanol | 0,015 | external energy input (MJ/MJ final fuel) | (Joint Research Center - European commission, 2008a) – SCET pathway |
| | soybeans | 0,073 | external energy input (MJ/MJ final fuel) | (Joint Research Center - European commission, 2008a) – SYFA pathway |
| | sugarcane | 0,018 | external energy input (MJ/MJ final fuel) | (Joint Research Center - European commission, 2008a) – SCET pathway |
| | switchgrass | 0,008 | external energy input (MJ/MJ final fuel) | (Joint Research Center - European commission, 2008a) – STET pathway |

| | | | | |
|---|---|---|---|---|
| **conversion energy** | Soybean diesel | 0,12 | external energy input (MJ/MJ final fuel) | (Joint Research Center - European commission, 2008a) – SYFA pathway |
| | sugarcane ethanol (including heat credit) | -0,14 | external energy input (MJ/MJ final fuel) | (Joint Research Center - European commission, 2008a) – SCET pathway |
| | switchgrass ethanol (including electricity credit) | -0,18 | external energy input (MJ/MJ final fuel) | (Joint Research Center - European commission, 2008a) – STET pathway |
| **energy in lost feedstock** | Soybean diesel (in fuel conversion) | 0,05 | feedstock energy (MJ/MJ final fuel) | (Joint Research Center - European commission, 2008a) – SYFA pathway |
| | Soybean diesel (as animal feed) | 2,00 | feedstock energy (MJ/MJ final fuel) | (Joint Research Center - European commission, 2008a) – SYFA pathway |
| | sugarcane ethanol | 1,772 | feedstock energy (MJ/MJ final fuel) | (Joint Research Center - European commission, 2008a) – SCET pathway |
| | switchgrass ethanol | 0,97 | feedstock energy (MJ/MJ final fuel) | (Schmer et al., 2008)(Pimentel & Patzek, 2005)(Energy Centre of the Netherlands (ECN), ) |

**Table 8: Input data of pathway energy.**

| Category | Parameter | Value | unit | Reference |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| **cultivation GHG emissions** | soybeans (including soybean meal) | 56,4 | g CO2/MJ final fuel | (Joint Research Center - European commission, 2008b) |
| | soybean oil mill | 2,80 | g CO2/MJ final fuel | (Joint Research Center - European commission, 2008a) – SYFA + WTET (steam generation) pathway; GEMIS |
| | sugarcane | 14,45 | g CO2/MJ final fuel | (Joint Research Center - European commission, 2008b); (Joint Research Center - European commission, 2008a) – SYFA pathway |
| | switchgrass | 9,02 | g CO2/MJ final fuel | (Smeets et al., 2009); (Joint Research Center - European commission, 2008a) – STET pathway; GEMIS |
| | | | | |
| **transport GHG emissions** | sugarcane and switchgrass ethanol | 1,5 | g CO2/MJ final fuel | (Smeets et al., 2009);(Joint Research Center - European commission, 2008a) – SCET pathway |
| | soybeans | 7,3 | g CO2/MJ final fuel | (Smeets et al., 2009);(Joint Research Center - European commission, 2008a) – SYFA pathway |
| | sugarcane | 1,8 | g CO2/MJ final fuel | (Smeets et al., 2009); (Joint Research Center - European commission, 2008a) – SCET pathway |
| | switchgrass | 0,8 | g CO2/MJ final fuel | (Smeets et al., 2009); (Joint Research Center - European commission, 2008a) – STET pathway |
| | | | | |
| **conversion GHG emissions** | Soybean diesel | 4,74 | g CO2/MJ final fuel | (Joint Research Center - European commission, 2008a) – SYFA pathway |
| | sugarcane ethanol (including heat credit) | -10,31 | g CO2/MJ final fuel | (Joint Research Center - European commission, 2008a) – SCET pathway |

| | | | | |
|---|---|---|---|---|
| | switchgrass ethanol (including electricity credit) | -4,36 | g CO2/MJ final fuel | (Smeets et al., 2009); (Joint Research Center - European commission, 2008a) – STET pathway; GEMIS |

**Table 9: Input data of pathway GHG emissions.**

| Category | Parameter | Value | unit | Reference |
|---|---|---|---|---|
| **transport distances** | ethanol | 300 | km | (Muzio et al., 2008) |
| | raw feedstock: soybeans | 300 | km | (Muzio et al., 2008) |
| | raw feedstock: sugarcane | 20 | km | (Joint Research Center - European commission, 2008a) – SCET pathway |
| | raw feedstock: switchgrass | 50 | km | (Joint Research Center - European commission, 2008a) – STET pathway |
| | | | | |
| **other** | CO2 emission diesel | 100,11 | g CO2/MJ diesel input | (Smeets et al., 2009) |
| | primary energy of diesel | 1,3 | MJ/MJ diesel | |
| | soybean oil content | 0,188 | mass fraction | |

**Table 10: Other pathway input data.**

| | Production (tonnes in 2007) | Export (tonnes in 2007) | land indicator (m2/year/kg) |
|---|---|---|---|
| **pig meat** | 230.000 | N/A | 8,9 |
| **cattle meat** | 2.830.400 | 358.566 | 20,9 |
| **milk (powder)** | 10.325.465 | 780.954 | 1,2 |
| **chicken meat** | 1.159.200 | 151.048 | 7,3 |
| **eggs** | 480.000 | N/A | 3,5 |

**Table 11: Livestock production (FAOSTAT 2007), export (FAOSTAT 2007) and relative land use** (Gerbens-Leenes et al., 2002)

# 4 Results

## 4.1 Biofuel production pathway analysis

The energy and GHG balance involves input energy of the feedstock and external input energy from fossils (directly as a fuel or indirectly as a product). The output of the balance is the final fuel, but there are also secondary output streams that are valuable as products outside the boundaries of this research, e.g. soybean meal as animal feed, or electricity output. These waste streams are accounted for by awarding primary energy and GHG emission credits.

### 4.1.1 Feedstock conversion losses

Feedstock energy is lost due to various inefficiencies in conversion processes. In case of soybean conversion to soybean diesel, only the oil fraction of the feedstock is used for biofuel conversion, the rest has a purpose as animal feed. In the switchgrass ethanol production pathway, feedstock energy is lost in the processes of conversion by fermentation. In ethanol production from sugarcane a large share of feedstock is lost in the sugar mill to remove the high moisture contents of the sugarcane, and also in the processes of fermentation. The calculated conversion efficiencies that have been used to calculate the final potential from raw feedstock are shown in Table 12 .

| | | GJ in final fuel /tonne Fresh matter |
|---|---|---|
| **soybean diesel** | 34,4% | 6,9 |
| **sugarcane ethanol** | 36,1% | 2,1 |
| **switchgrass ethanol** | 50,7% | 9,1 |

**Table 12: conversion efficiency final fuel energy/feedstock energy (see 3.8 *Data Input* for sources)**

### 4.1.2 Energy and GHG balance

The energy balance of the biofuel pathway gives an indication of the energetic efficiency of the biofuel potential. Table 13, Table 14 and Table 15 give an overview of the energy inputs per energy unit of the final fuel. Separate columns are used to distinguish external energy inputs from feedstock losses. This distinction is made because external energy inputs are fossil while the lost feedstock is renewable and has therefore no associated GHG emissions. The feedstock energy content and feedstock losses determine the final energy potential. The GHG emissions that are shown arise from external energy and chemical inputs and also include negative emission (credits) for electricity production (switchgrass), heat recovery (sugarcane) and wheat replacement (soybean). The GHG balance is used to calculate the potential emission reduction of the fresh weight potential.

As can be seen in the tables, there are strong differences, primarily between the energetic efficiency of soybean diesel and the other 2 biofuel pathways. Soybean diesel production is energetically highly inefficient, with external energy inputs that almost equal the energy content of the final fuel. For the other two pathways, the external energy input is near zero. This does not mean that there are no fossil energy inputs, but that the energy benefits of 'waste' streams from conversion processes outweigh the energy inputs throughout the production pathway. This waste energy can be used to produce electricity or useful heat, and thereby save fossil energy elsewhere. Whether or not a low external energy input results in a high effective biofuel energy potential equally depends on the yield performance of the feedstock and the loss of feedstock. With the inclusion of feedstock losses, soybean diesel remains the least efficient, whereas switchgrass ethanol has the best energetic performance. The main reason for the poor performance of soybean biodiesel is the double function of the soybean crop, producing both oil and soy meal as main products. However, the energy input covers both products but are fully allocated to biodiesel production. This overlap in functions is accounted for in the GHG emission balance by awarding credits for avoided emissions. This is done for soybean diesel, by accounting for the replacement of dedicated animal feed production. In the sugarcane production process, credit is awarded to account for the replacement of heavy fuel oil production by processed excess bagasse. Considering the GHG emission balance, the order of performance between the pathways remains unchanged. The net GHG emissions compared to the fossil fuel alternative are negative for all pathways, although much less for soybean diesel than the other 2 pathways.

| Imported soy beans, glycerine as chemical, soya meal replaces wheat | external energy input (MJ/MJ final fuel) | external energy input + feedstock loss (MJ/MJ final fuel) | net GHG emitted (g/MJ final fuel) |
|---|---|---|---|
| **cultivation** | 0,05 | 0,05 | 10,60 |
| **bean transport (300 km)** | 0,01 | 0,01 | 1,37 |
| **oil mill** | 0,07 | 0,07 | 2,80 |
| **fame manufacture** | 0,12 | 0,17 | 4,74 |
| **total net fossil energy inputs** | **0,25** | **0,30** | **19,5** |
| | | | |
| **minus renewable fuel credits of 71,4 g/MJf** | | | **-51,9** |

**Table 13: Energy inputs and carbon emission balance – soybean diesel**

| EtOH from sugar cane (Brazil), HFO credit for excess bagasse | external energy input (MJ/MJ final fuel) | external energy input + feedstock loss (MJ/MJ final fuel) | net GHG emitted (g/MJ final fuel) |
|---|---|---|---|
| **cultivation** | 0,06 | 0,06 | 14,45 |
| **road transport (20 km sugarcane, 300 km** | 0,03 | 0,03 | 2,72 |

| | | | |
|---|---|---|---|
| **ethanol)** | | | |
| **ethanol plant** | -0,14 | 1,63 | -10,31 |
| **total net fossil energy inputs** | **-0,05** | **1,72** | **7,68** |
| | | | |
| **minus renewable fuel credits of 71,4 g/MJf** | | | **-63,72** |

**Table 14: Energy inputs and carbon emission balance – sugarcane ethanol**

| **switchgrass** | **external energy input (MJ/MJ final fuel)** | **external energy input + feedstock loss (MJ/MJ final fuel)** | **net GHG emitted (g/MJ final fuel)** |
|---|---|---|---|
| **cultivation** | 0,13 | 0,13 | 9,02 |
| **road transport (50 km switchgrass, 300 km ethanol)** | 0,02 | 0,02 | 2,23 |
| **ethanol plant** | -0,18 | 0,79 | -4,36 |
| **total net fossil energy inputs** | **-0,03** | **0,94** | **6,9** |
| | | | |
| **minus renewable fuel credits of 71,4 g/MJf** | | | **-64,5** |

**Table 15: Energy inputs and carbon emission balance – switchgrass ethanol**

Although this balance provides a good indication of the pathways' energetic efficiency and GHG emissions, an additional parameter is required to determine the GHG emission mitigation potential. This parameter is the fresh weight potential of the feedstock, and is used to calculate the Energy potential and potential GHG emission savings. The results of this are elaborated in the next paragraph.

## 4.2 Geographic potential and land use class potential

### 4.2.1 Potential in fresh weight

The production potential per crop looks such as shown in the graphs of Figure 5. All graphs share one thing in common. The highest potential is typically located in the Northeast of the country, which is where the pampas area and other agricultural areas are located. This is a logic consequence of the very profitable climatic conditions with high temperatures and precipitation. The higher variation of soy yields in the northwest is caused by the projection of current yields over the potential map. The yield potential of sugarcane shows very clearly how strongly it relies on irrigation, as the potential is nearly absent except in the utter northwest, due to the lack of rainfall. Note that this is a theoretical maximum that does not involve land use constraint within Argentina. Also, it should be noted that the yield performance between the different feedstock types varies strongly and does not account for energy content as well as energy inputs and losses during the biofuel production pathway.

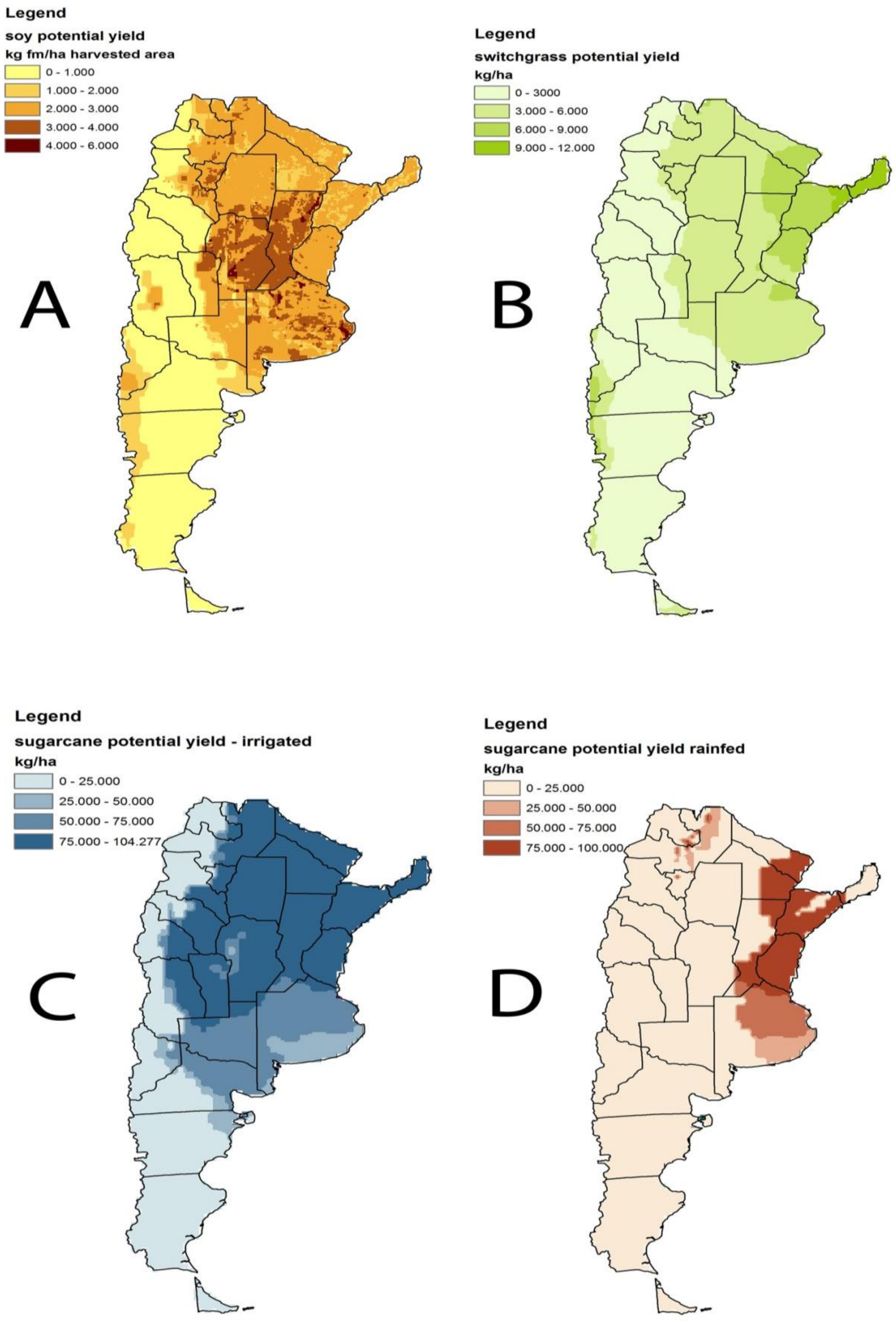


**Figure 5: current Geograpic potential yield in kg/ha of feedstock for soy, switchgrass, sugarcane irrigated and sugarcane rain fed, visualized in part A, B, C and D respectively. (Kg/ha)**

The total area per land class is shown in Table 16. In Table 17 it is shown how the fresh weight potential is related to the type of land class. Also, all other constraints are included in the result of this table. The differences in potential per land use class illustrate the differences in potential yield of these areas. Concerning Soybeans, Switchgrass and sugarcane irrigated, the classes of cropland, shrubland and forest account for around 90% of the geographic fresh weight potential whereas this is 86% for rain fed sugarcane. It can be seen that the current potential, which only involves the land class of sparsely vegetated area (highlighted in green) is very low compared to the area of this land class. For this reason it is decided to consider current potential as zero. The potential on cropland and shrubland represents a theoretical maximum, of which a part can be obtained in future potential due to increases in agricultural efficiency and diet change (highlighted in yellow). The theoretic maximum is thereby around 60% of the geographic potential.

| | *1000 hectares | |
|---|---|---|
| **cropland** | 42.336 | 15,9% |
| **shrubs** | 91.956 | 34,6% |
| **forest** | 69.225 | 26,0% |
| **sparseveg** | 32.630 | 12,3% |
| **flooded** | 7.019 | 2,6% |
| **iced** | 581 | 0,2% |
| **barearea** | 19.212 | 7,2% |
| **urban** | 162 | 0,1% |
| **water** | 2.968 | 1,1% |
| **total** | 266.091 | |

**Table 16: area per land use class in Argentina in 2007.**

| potential share per type of land class | Soybeans | Switchgrass | Sugarcane irrigated | Sugarcane rainfed |
|---|---|---|---|---|
| **cropland** | 28,3% | 27,0% | 23,4% | 36,7% |
| **shrubland** | 32,4% | 34,2% | 39,7% | 23,3% |
| **forest** | 29,6% | 27,3% | 27,9% | 25,6% |
| **sparseveg** | 2,2% | 3,9% | 2,0% | 0,1% |
| **flooded** | 4,3% | 4,9% | 3,8% | 13,2% |
| **iced** | 0,0% | 0,0% | 0,0% | 0,0% |
| **barearea** | 1,9% | 1,7% | 2,2% | 0,0% |
| **urban** | 0,1% | 0,1% | 0,1% | 0,3% |
| **water** | 1,1% | 1,0% | 0,8% | 0,8% |
| | | | | |
| **Total fresh weight potential in million tonnes/year** | 438 | 792 | 10457 | 98 |

**Table 17; Fresh weight potential in million tonnes/year and the relative contribution of Globcover land classes in 2007.**

In Figure 6, potential yield maps that account for all constraints are shown for all feedstock types. From the potential yield maps, the current fresh weight potential is calculated.

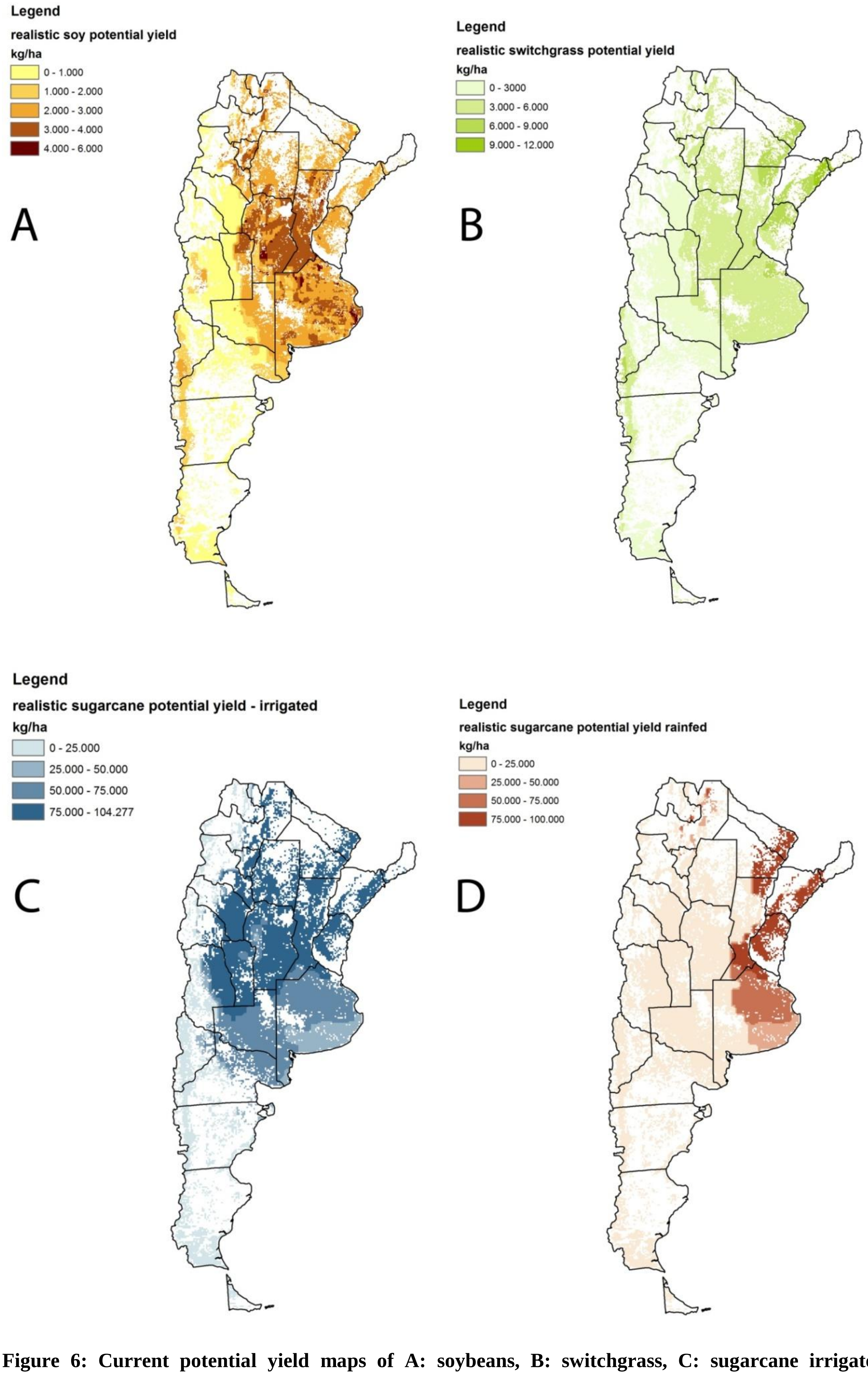


**Figure 6: Current potential yield maps of A: soybeans, B: switchgrass, C: sugarcane irrigated, C: sugarcane rain fed in 2007. (kg/ha)**

### 4.2.2 Potential in energy content

| | soybean | switchgrass | sugarcane irrigated | sugarcane rainfed |
|---|---|---|---|---|
| **cropland** | 610 | 1.422 | 2.118 | 31 |
| **shrubs** | 869 | 2.425 | 4.831 | 27 |
| **forest** | 758 | 1.971 | 3.457 | 30 |
| **sparseveg** | 41 | 282 | 252 | 0 |
| **flooded** | 110 | 355 | 475 | 15 |
| **iced** | 0 | 2 | 1 | 0 |
| **barearea** | 23 | 121 | 278 | 0 |
| **urban** | 2 | 6 | 9 | 0 |
| **water** | 25 | 70 | 101 | 1 |
| **sum** | 2.438 | 6.654 | 11.521 | 105 |

**Table 18: Potential in energy content per feedstock type in 2007 (PJ/year)**

### 4.2.3 Potential in CO2 emission reduction

| | soybean | switchgrass | sugarcane irrigated | sugarcane rainfed |
|---|---|---|---|---|
| **cropland** | 31.649 | 91.710 | 134.942 | 1.995 |
| **shrubs** | 45.070 | 156.418 | 307.847 | 1.700 |
| **forest** | 39.331 | 127.125 | 220.295 | 1.909 |
| **sparseveg** | 2.138 | 18.173 | 16.028 | 6 |
| **flooded** | 5.717 | 22.906 | 30.251 | 987 |
| **iced** | 15 | 116 | 60 | 0 |
| **barearea** | 1.176 | 7.801 | 17.690 | 0 |
| **urban** | 117 | 414 | 591 | 25 |
| **water** | 1.318 | 4.538 | 6.446 | 59 |
| **sum** | 126.532 | 429.201 | 734.151 | 6.680 |

**Table 19: GHG emission reduction potential per feedstock type in 2007 (1000*tonnes/year)**

## 4.3 Model comparison

### 4.3.1 Crop allocation patterns

The production results of the homogeneous allocation are compared with required production levels in 2007, such as shown in Table 20. The "Best suitability" allocation model is used to allocate crops on best suitable locations. Yield maps have been calibrated with the area maps from this allocation model to match production statistics of 2007. The results of this model thus function as a reference. Considering that allocation using that method is already optimal, the homogeneous allocation model is expected to render 'less optimal' results, i.e. a lower crop production by the same quantity of land area. Although it appears from the results that 5 out of 6 crops result in a lower production, cereal production is higher than by using suitability allocation. This means that in the "best suitability" allocation model, cereals are not always allocated on the best locations, as is also visible when comparing the allocated area maps with yield maps. The suitability allocation model is used to calculate all scenarios of future potential.

| | homogenous | best suitable | difference | relative difference |
|---|---|---|---|---|
| **cereal** | 43.839.720 | 37.962.341 | 5.877.379 | 15,5% |
| **oil** | 45.953.117 | 51.651.507 | -5.698.390 | -11,0% |
| **pulses** | 246.615 | 337.179 | -90.564 | -26,9% |
| **fibres** | 2.490.408 | 2.829.032 | -338.624 | -12,0% |
| **cotton** | 406.071 | 545.382 | -139.311 | -25,5% |
| **rice** | 453.025 | 1.080.070 | -627.045 | -58,1% |
| | | | | |
| **total** | 93.388.956 | 94.405.511 | -1.016.555 | |

**Table 20: Crop production of homogeneous vs 'best suitability' allocation, using yield maps that are calibrated with the the area maps of the best suitability model (current situation). (tonnes/year)**

Differences in allocation distribution between the two methods are visually presented in the figures on the next pages.

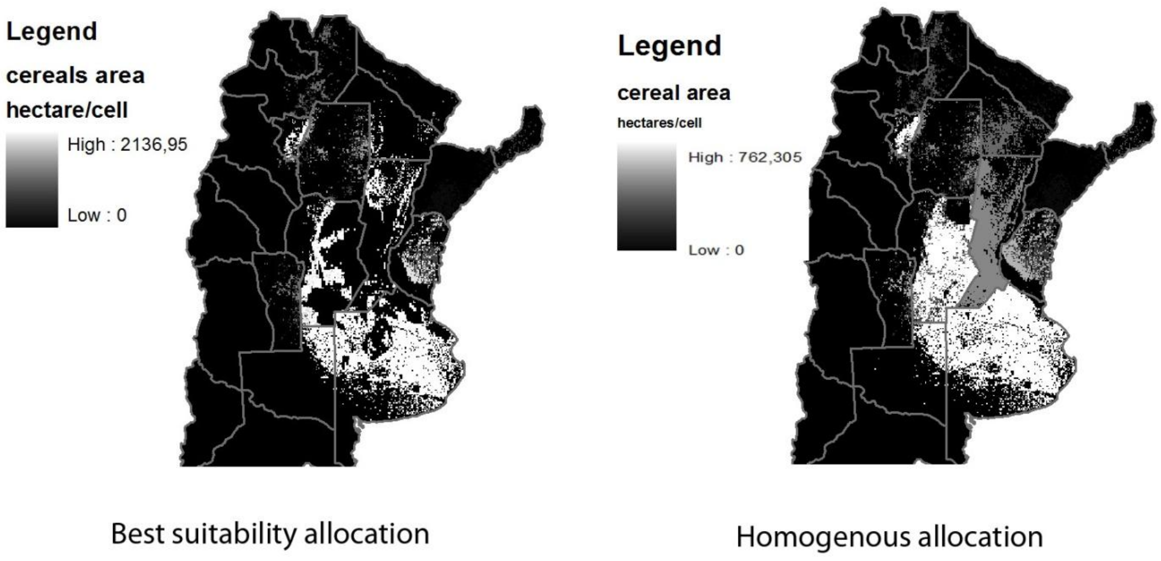


**Figure 7: Suitability allocation model vs Homogeneous method - cereals**

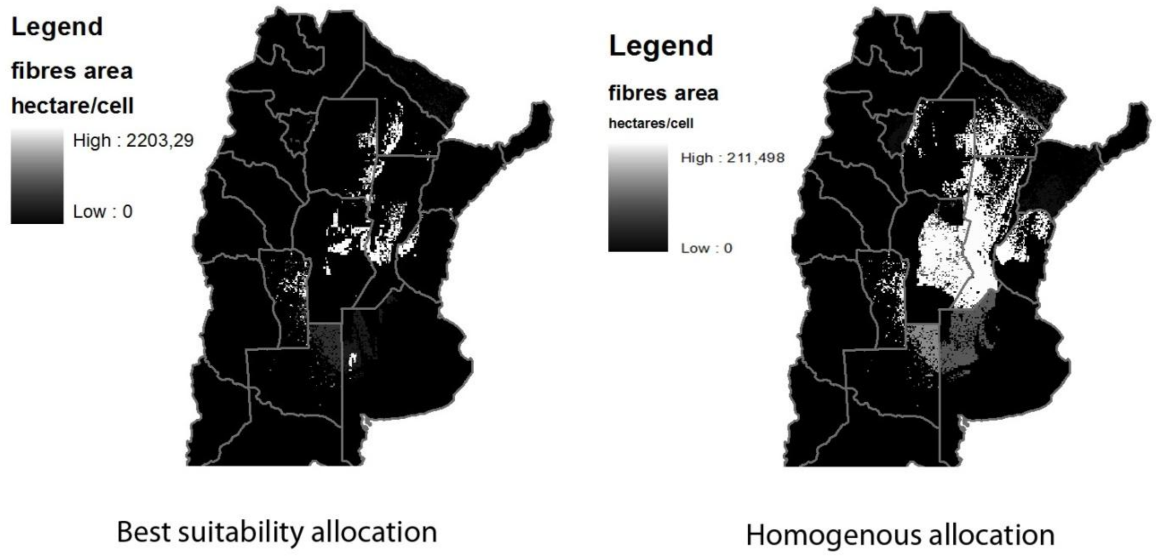


**Figure 8: Suitability allocation model vs Homogeneous method – fibres**

Note the differences in Legend range while interpreting the figures. Comparing the crop distribution pattern of the 2 models shows that the allocated area of the suitability allocation model is concentrated on high suitability areas, whereas homogenous allocation shows even distribution on all areas with a suitability greater than zero. However as mentioned earlier, in case of cereals, the suitability allocation model appears to <u>not</u> always allocate on the best locations.

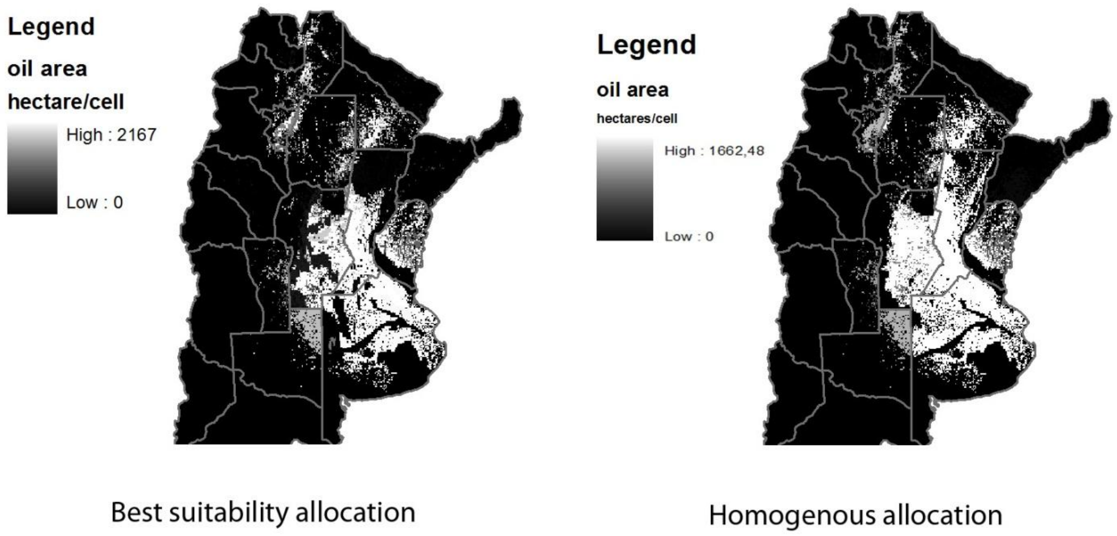


**Figure 9: Suitability allocation model vs Homogeneous method – oil crops**

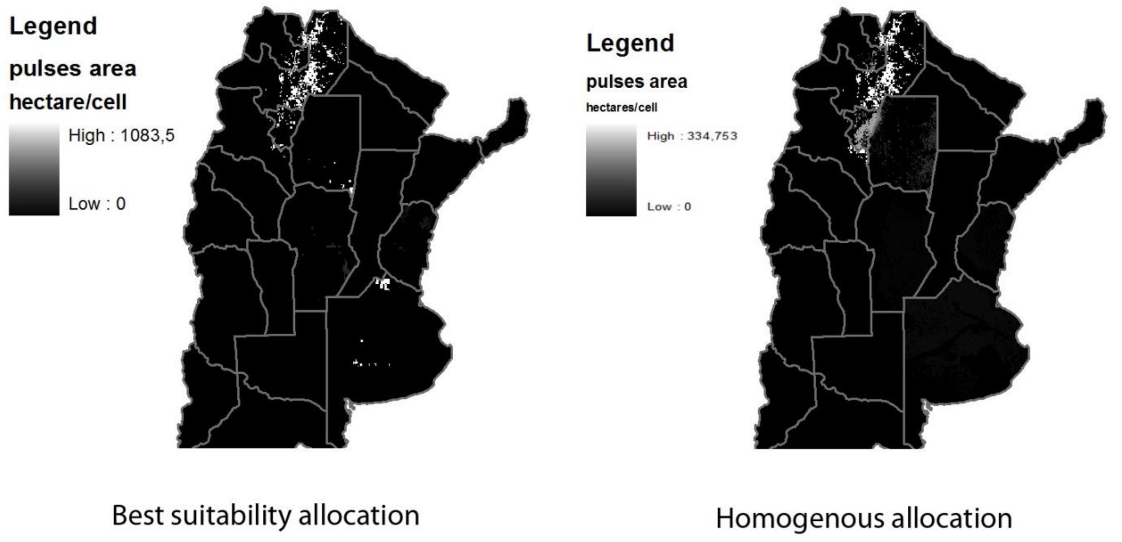


**Figure 10: Suitability allocation model vs Homogeneous method - pulses**

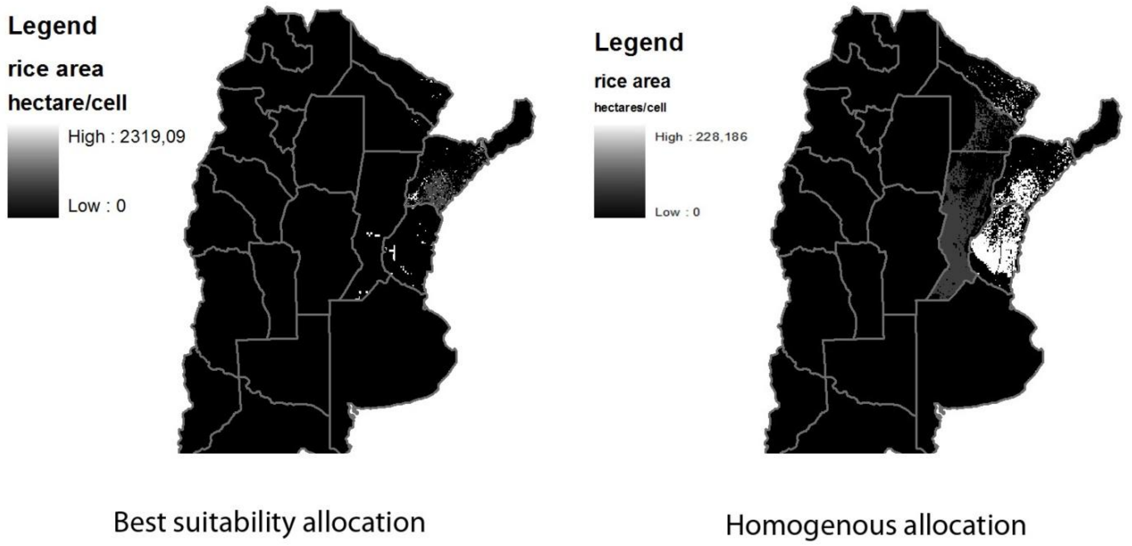


**Figure 11: Suitability allocation model vs Homogeneous method - rice**

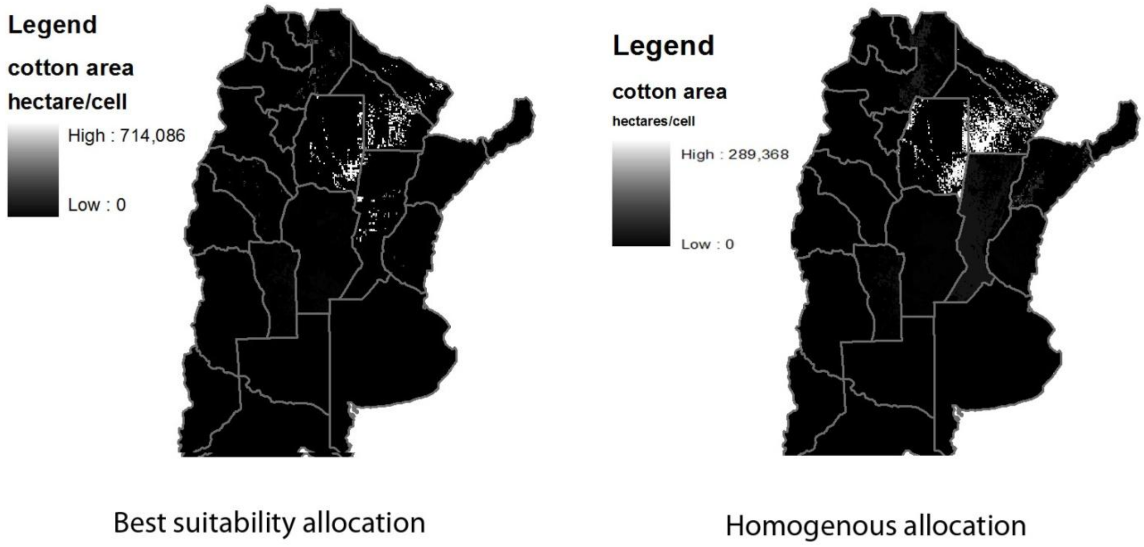


**Figure 12: Suitability allocation model vs Homogeneous method - cotton**

### 4.3.2 Future potential – results

Due to the perceived low geographic and land use class potential of sugarcane in Argentina under rainfed conditions, sugarcane is no longer considered for future potential calculations.

Biofuel potential on cropland as calculated by the suitability allocation model – province run is shown in Table 21. Results of the homogeneous allocation model are shown in Table 22.

| Potential using the 'Best suitability' model | soybean | switchgrass |
|---|---|---|
| **2015** | 8.987 | 17.594 |
| **2030** | 41.263 | 82.884 |

**Table 21: Biofuel potential in tonnes/year * 1000, using the 'Best suitability model'**

Determining available land for biofuel in future situation requires a reference situation (2007) for which production levels of all crops exactly match demand. However this is not the case as the homogeneous allocation model shows deficit as well as surplus for different crops in its allocated quantities. The homogeneous allocation model has been used to match area statistics, but does not match production statistics. Therefore correction factors are applied to the area maps to match production statistics (and thus not area statistics). Available land in future situation is then determined by allocating a fraction of the previously calculated area maps that equals the assumed efficiency increases in 2015 and 2030, minus 2,5% (the extent to which homogeneous allocation appeared less effective than suitability allocation).

| Potential using the 'homogenous allocation' model | soybean | switchgrass |
|---|---|---|
| **2015** | 5.297 | 10.340 |
| **2030** | 38.275 | 74.719 |

**Table 22: Biofuel potential in tonnes/year * 1000, using the 'Homogeneous allocation model'**

A visual presentation of the results is given in Figure 13 and Figure 14 for the suitability allocation model and homogeneous allocation method respectively.

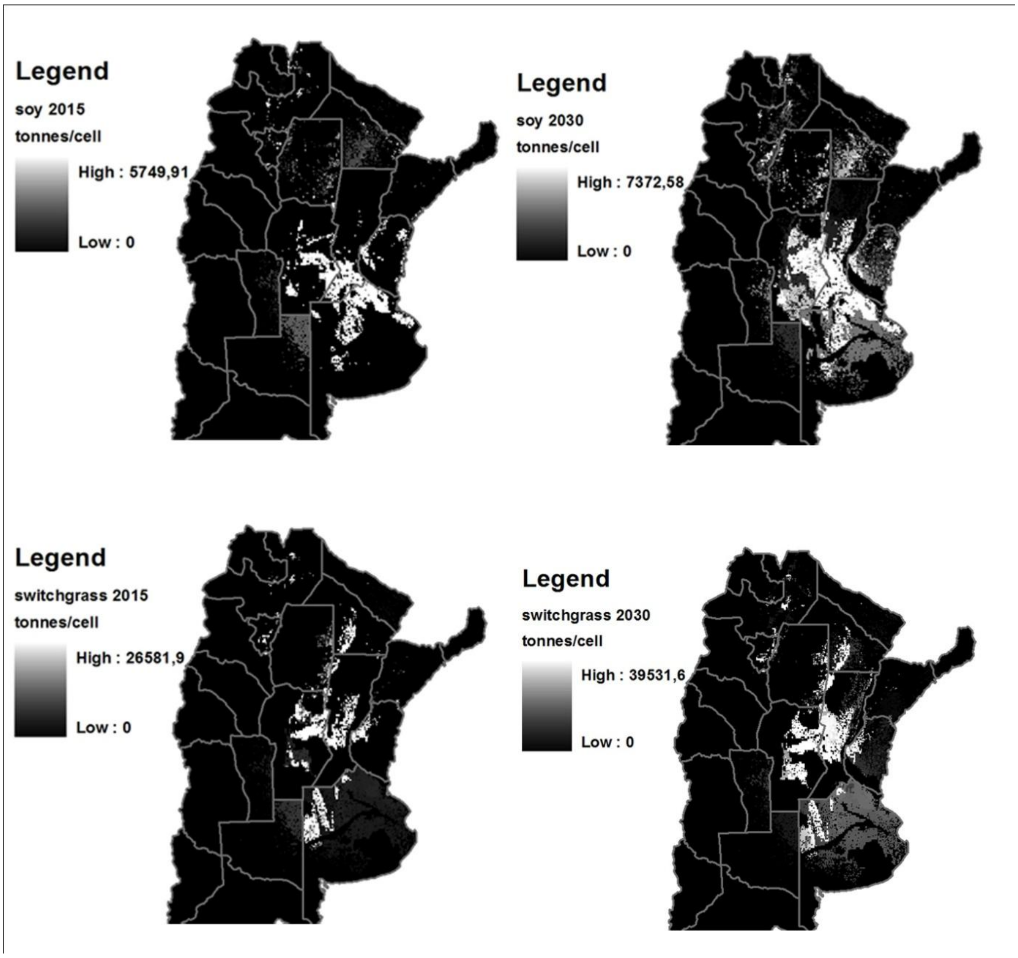


**Figure 13: Suitability allocation model – crop distribution patterns (tonnes/cell).**

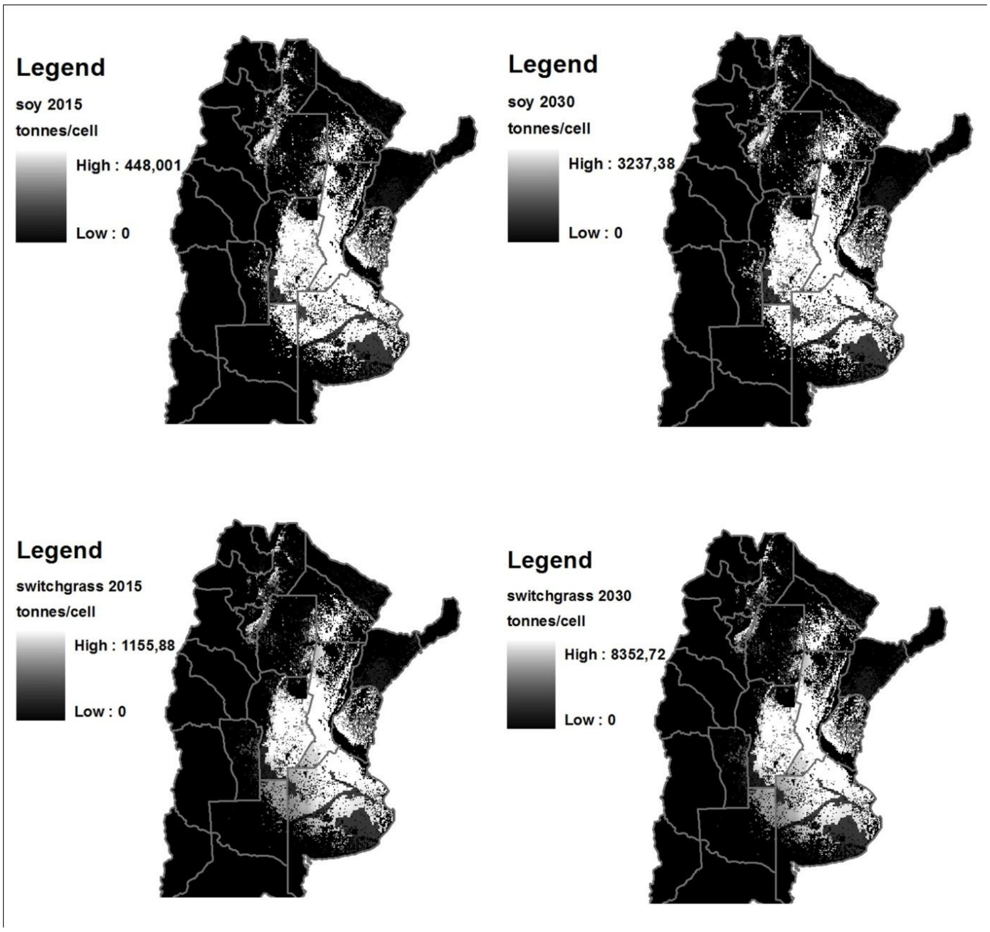


**Figure 14: Homogeneous allocation method – crop distribution patterns (tonnes/cell).**

The results of the model runs on nation level statistics involving 8 yield growth variations for switchgrass and soy and how this relates to province level runs are elaborated in 4.5 Efficiency growth sensitivity (nation level – suitability allocation).

## 4.4 Efficiency growth sensitivity (Buenos Aires)

For the province of Buenos Aires the main model (suitability allocation) has been used using 4 different input values of efficiency growth rates between 1 and 2 % annually. This involves running the model 14 times with different input data. Although parameter variation can lead to much better insight in the performance of the model, it has been decided not to do this on a national level, as this would require the model to run 224 times, regarding this parameter alone. The results are shown in Table 23. As can be seen a 1% growth rate is too low to generate any potential in 2015 since yield growth is not strong enough to counteract the rising demand for food due to population growth.

| annual growth rate | soy 2015 | soy 2030 | switchgrass 2015 | switchgrass 2030 |
|---|---|---|---|---|
| **1%** | 0 | 3.575 | 0 | 5.543 |
| **1,33%** | 1.543 | 5.580 | 2.141 | 15.104 |
| **1,67%** | 2.984 | 13.285 | 4.653 | 24.020 |
| **2%** | 4.374 | 17.325 | 7.126 | 31.936 |

**Table 23: Biofuel potential on cropland vs. annual yield growth – Buenos Aires. Units are in tonnes/year.**

In Table 24 it is shown how strongly increases in growth rate affect potential biofuel production. On the short term (2015), parameter sensitivity seems to be more or less constant whereas 2030 values shows some more variation. Since the potential production depends on varying spatial yield levels as well as varying location it was not expected to perceive a clear pattern of sensitivity. However, it should also be noted that the range of parameter variation is too low to draw conclusions on this.

| annual growth rate | Soy 2015 | soy 2030 | switchgrass 2015 | switchgrass 2030 |
|---|---|---|---|---|
| **1%** | N/A | N/A | N/A | N/A |
| **1,33%** | 1.543 | 2.005 | 2.141 | 9.562 |
| **1,67%** | 1.440 | 7.705 | 2.512 | 8.916 |
| **2%** | 1.390 | 4.040 | 2.473 | 7.916 |

**Table 24: Biofuel potential – parameter sensitivity on cropland vs. annual yield growth – Buenos Aires. Units are in tonnes/year and relative to the procuring growth rate.**

A visual presentation of the sensitivity results for parameter assumptions) is given in Figure 15 and Figure 16 for soybean and switchgrass respectively.

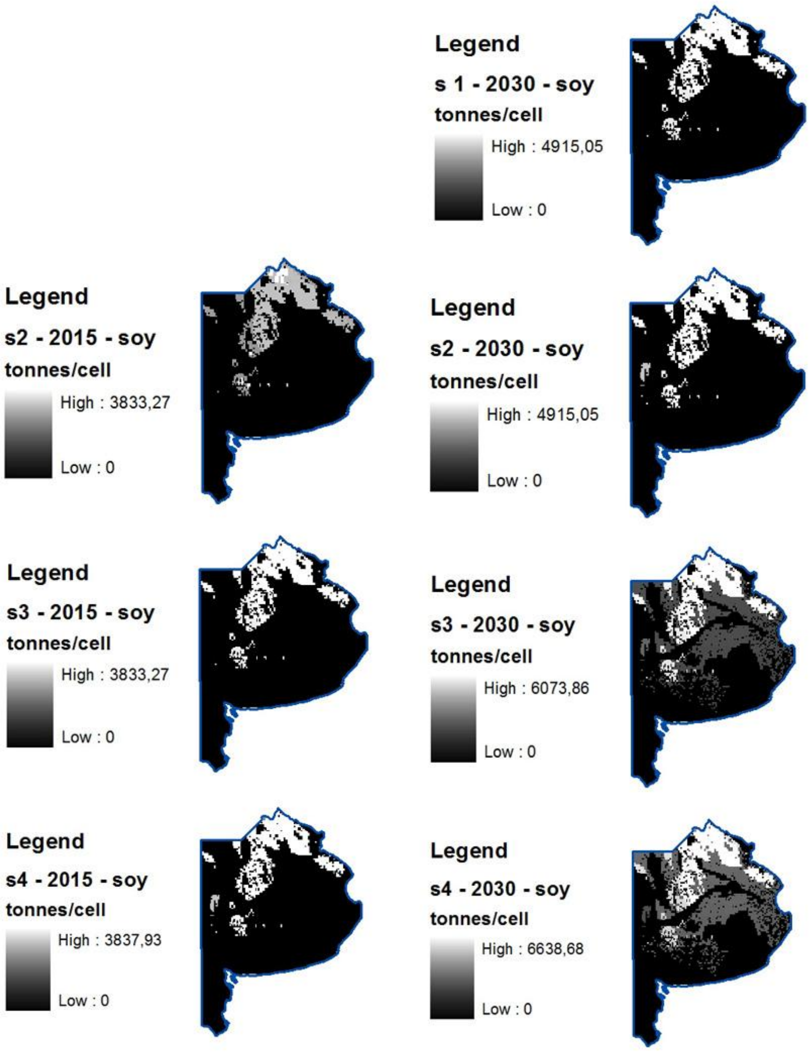


**Figure 15: Buenos Aires soybean biofuel allocation – sensitivity to efficiency increase level. (units in hectares/cell)**

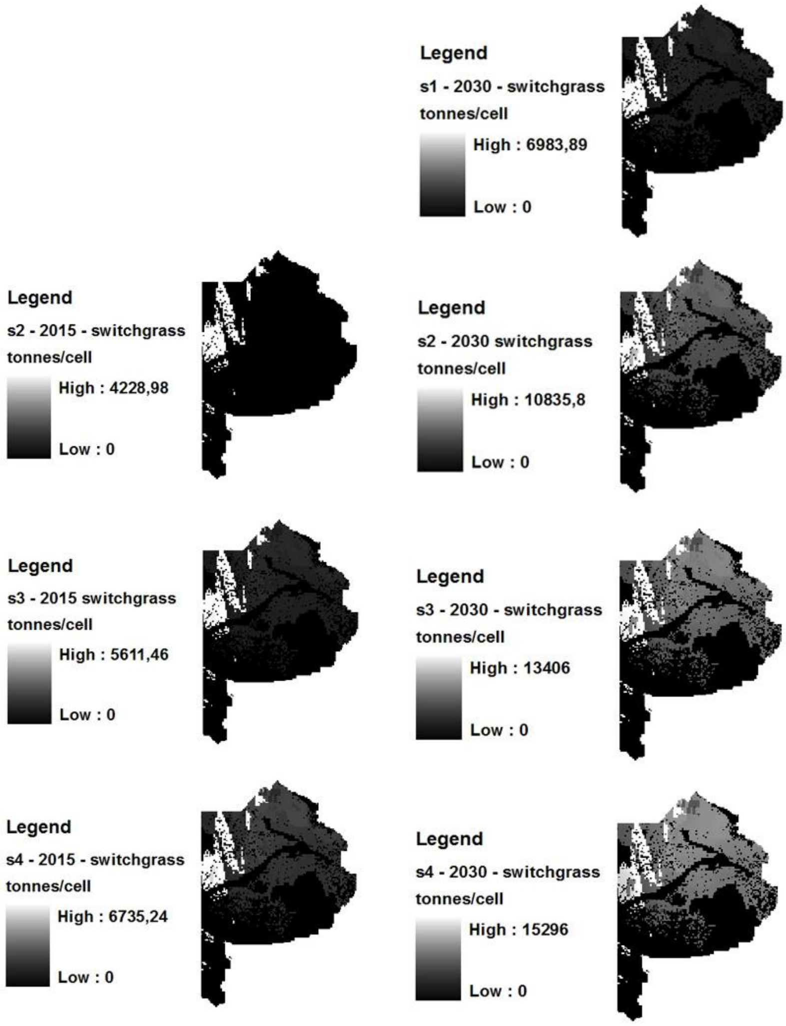


**Figure 16: Buenos Aires switchgrass biofuel allocation – sensitivity to efficiency increase level. (units in hectares/cell)**

The visual distribution patterns that emerge signify concentration of potential on a limited number of locations for low growth rates and expansion to surrounding areas at higher growth rates. The rationale behind allocation based on suitability would lead to expect that the latter locations have lower yields than the former. However, this is not necessarily the case. Land of high suitability for biofuels that is freed up trough efficiency growth is in each model run again open for crop competition along with all other areas. Whereas biofuels may 'lose' competition on the most suitable released areas by low yield growth, high yield growth may release more suitable area for biofuels, since there less competition from regular crops.

## 4.5 Efficiency growth sensitivity (nation level – suitability allocation)

The modeling results are shown in Table 25. While yield growth that is used to determine allocation is varied over a range, the actual yield maps of biofuel performance are remained constant to isolate the effect of area quantity and quality on the result. Hence,  if increasing the yield growth factor leads to diminishing returns, it can be concluded that this is caused by a decrease in the quality if available area. Not in the quantity because this is fixed to the yield growth factor.

| **country model** | **annual growth (%)** | **soy** | **switchgrass** |
|---|---|---|---|
| **unit: megatonnes/year** | 1 | 11 | 23 |
| | 1,33 | 20 | 42 |
| | 1,67 | 41 | 86 |
| | 2 | 54 | 112 |
| | 2,333 | 65 | 135 |
| | 2,67 | 76 | 156 |
| | 3 | 85 | 175 |
| | 3,333 | 94 | 192 |
| | | | |
| **Province level run  (annual growth = 1,67)** | | 41 | 83 |

**Table 25: suitability allocation model results – country level run – growth rate variation**

Firstly these results show that a nation level model run leads to slightly higher potential for switchgrass in comparison to the 1,67% yield growth province run, whereas the results are the same for soy potential. Using nation level instead of province level area constraints provides more freedom for the model to select the best possible locations for allocation. Nation level allocation was thereby expected to yield better potential results. A possible explanations for this not being the case is that current distribution of crops over provinces is already quite efficient.

Regarding yield growth sensitivity analysis, the variation range is more than twice as large as earlier performed for the province runs of Buenos Aires.  This provides a better insight in how potential quantities respond to increases in yield growth rate. A visualization is given in Figure 17.

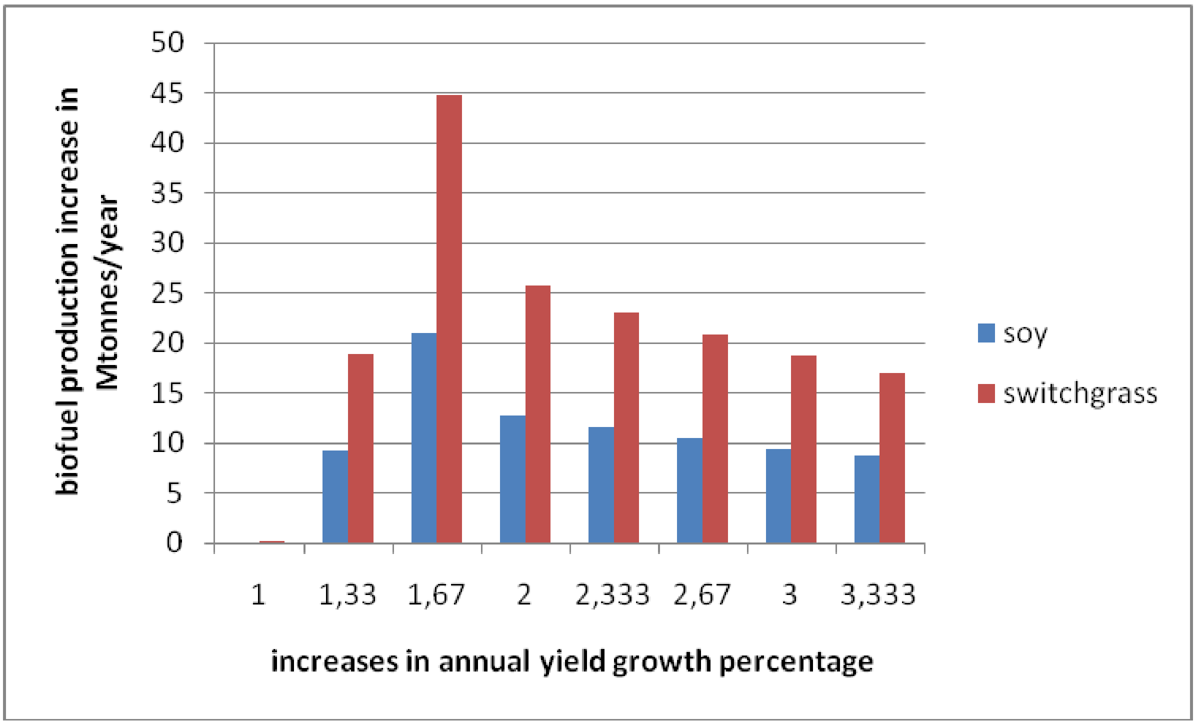


**Figure 17: potential biofuel production increase in Mtonnes/year (y axis) in respons to increases in annual yield growth percentage (x axis) , compared to the previous yield growth factor. Biofuel yields are remained constant for 1,67% growth.**

As can be seen from Figure 17, the potential returns peak at 1,67% growth rate and then slowly level off. This implies that although more land becomes available at high yield growth rates, the average quality goes down. This is a logical consequence of using suitability based allocation. If biofuel yields are applied the same variation as the yield growth used for area allocation, the effect of decreasing returns on the average suitability of available land is softened, but still visible, as shown in Figure 18.

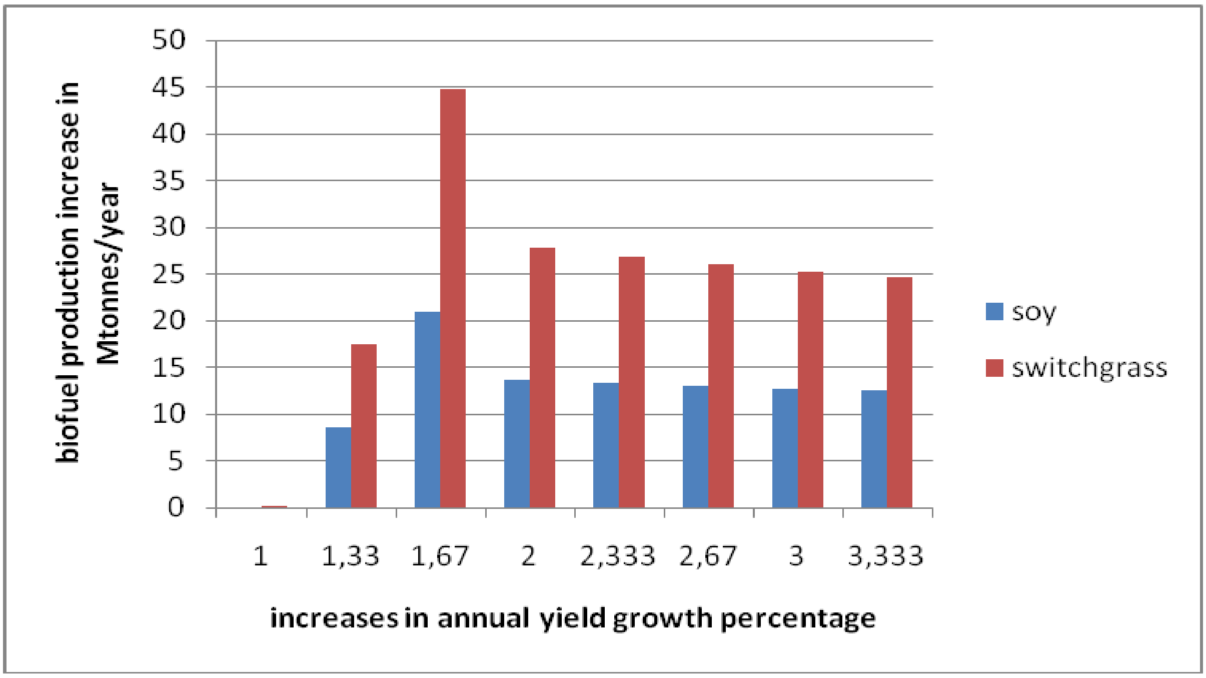


**Figure 18: potential biofuel production increase in Mtonnes/year (y axis) in respons to increases in annual yield growth percentage (x axis) , compared to the previous yield growth factor. Biofuel yields are applied the same yield growth as used for area allocation.**

A visual presentation of the shifting spatial distribution while increasing annual yield growth is given in the Figure 19 – Figure 26.

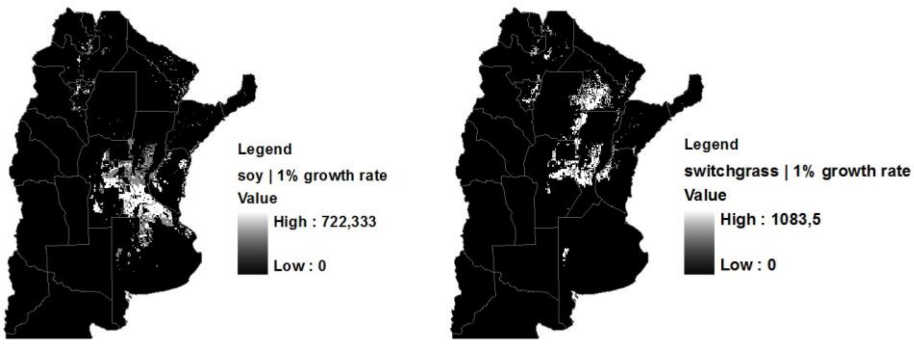


**Figure 19: suitability allocation model – nation level allocation 2030 – 1% annual yield growth – allocated biofuel area in hectares/cell**

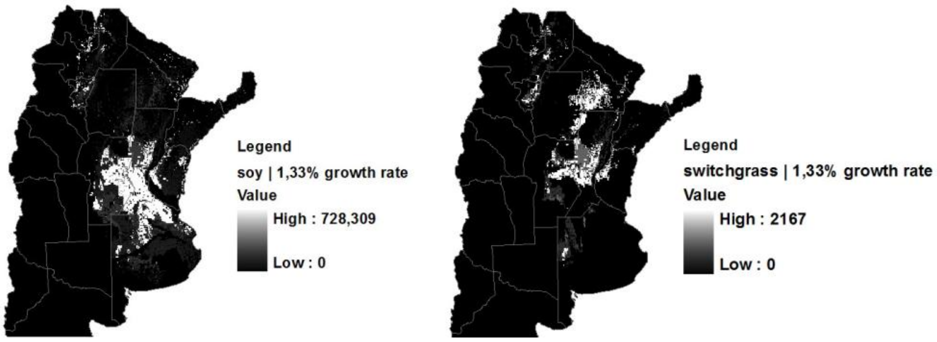


**Figure 20: suitability allocation model – nation level allocation 2030 – 1,33% annual yield growth – allocated biofuel area in hectares/cell**

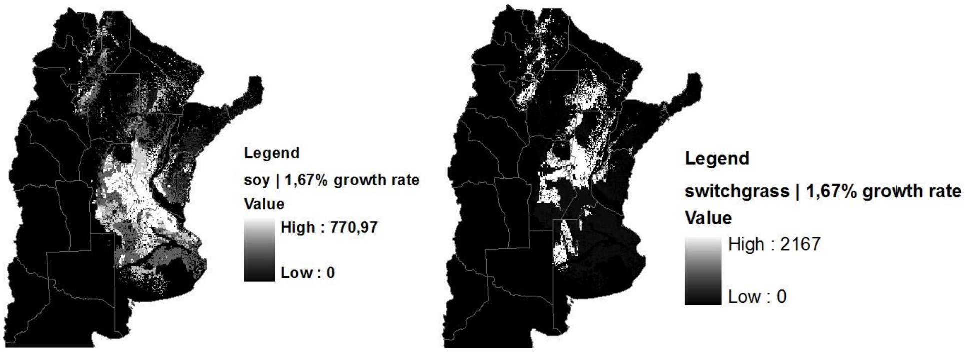


**Figure 21: suitability allocation model – nation level allocation 2030 – 1,67% annual yield growth – allocated biofuel area in hectares/cell**

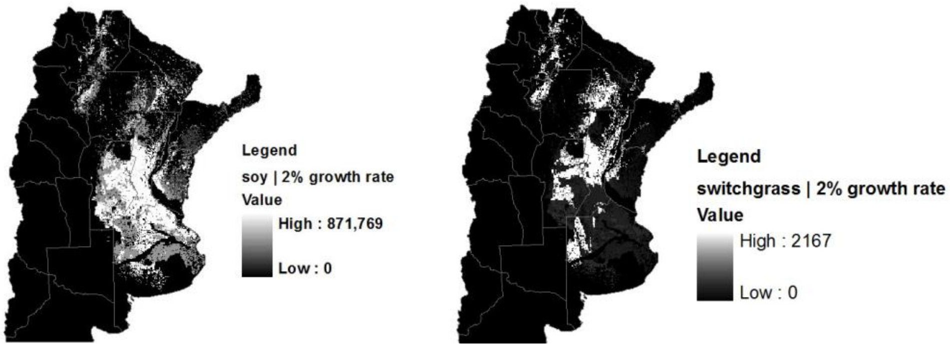


**Figure 22: suitability allocation model – nation level allocation 2030 – 2% annual yield growth – allocated biofuel area in hectares/cell**

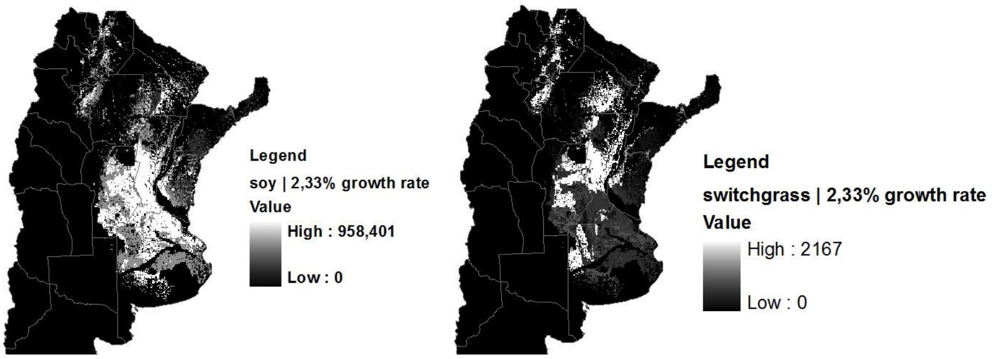


**Figure 23: suitability allocation model – nation level allocation 2030 – 2,33% annual yield growth – allocated biofuel area in hectares/cell**

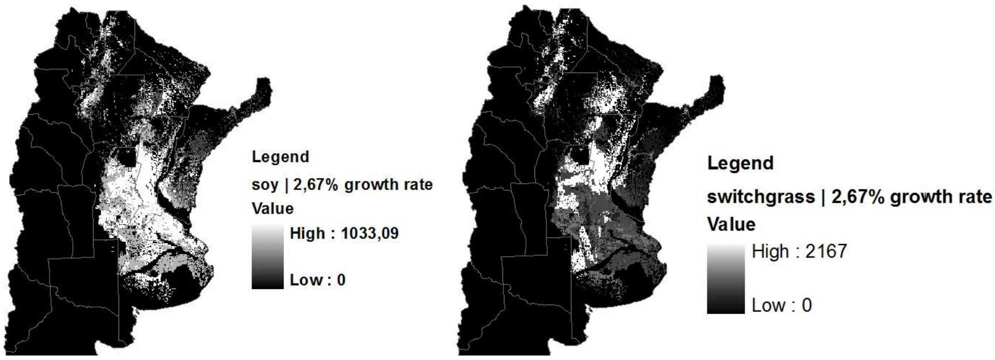


**Figure 24: suitability allocation model – nation level allocation 2030 – 2,67% annual yield growth – allocated biofuel area in hectares/cell**

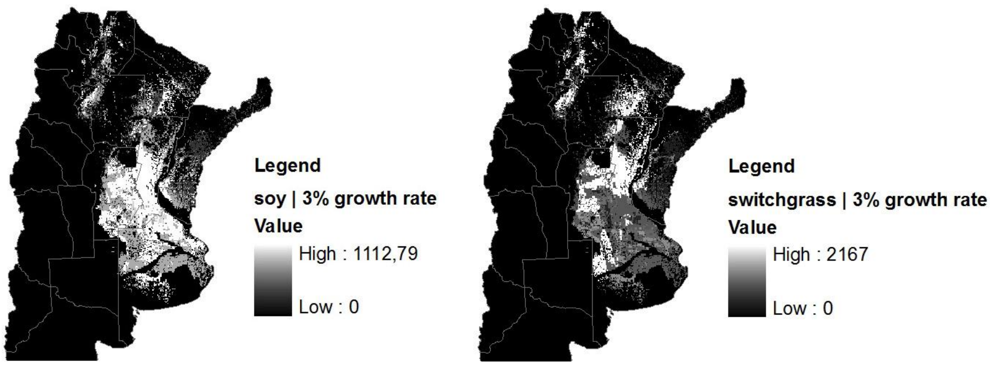


**Figure 25: suitability allocation model – nation level allocation 2030 – 3% annual yield growth – allocated biofuel area in hectares/cell**

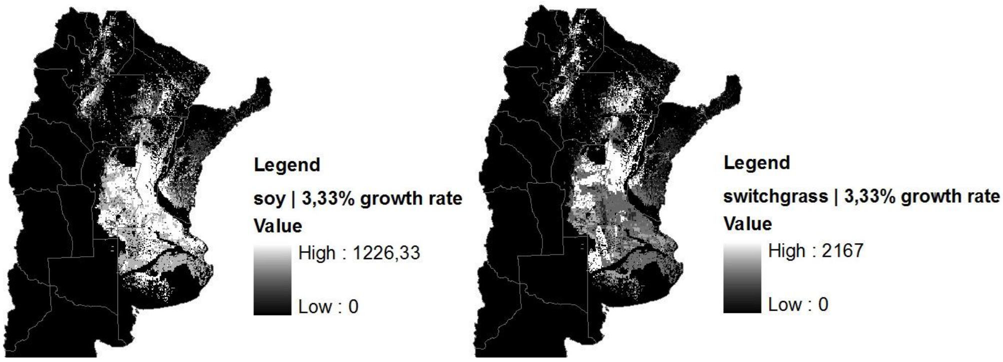


**Figure 26: suitability allocation model – nation level allocation 2030 – 3,33% annual yield growth – allocated biofuel area in hectares/cell**

## 4.6 Potential on pastures (country level)

For calculation of the biofuel potential on pasture area the result is based on baseline intensification and a theoretical maximum of intensification (Table 26), using the respective yields of 2015 and 2030. For soy, a distinction is made between rainfed and irrigated production, the latter reaching much higher production levels in the southern arid regions of Argentina. For switchgrass only rainfed production is considered, due to a lack of irrigated productivity data.

| | 2015 | 2030 |
|---|---|---|
| **soy rainfed - baseline** | 4.608 | 16.987 |
| **soy rainfed -max** | 67.558 | 86.624 |
| **soy irrigated - baseline** | 8.418 | 31.033 |
| **soy irrigated - max** | 123.420 | 158.250 |
| **switchgrass - baseline** | 9.762 | 35.986 |
| **switchgrass - max** | 143.120 | 183.509 |

**Table 26: Biofuel potential on free pasture areas (units in Mtonnes/year)**

In Figure 27 a visual presentation is given on the effect of irrigation on soybean potential. This clearly shows the broader extent of potential over Argentina or irrigated production. In Figure 28 it can be seen that raising the amount of available pastures is performed homogeneously. Scenarios that involve available pasture share variation are thereby not spatially explicit.

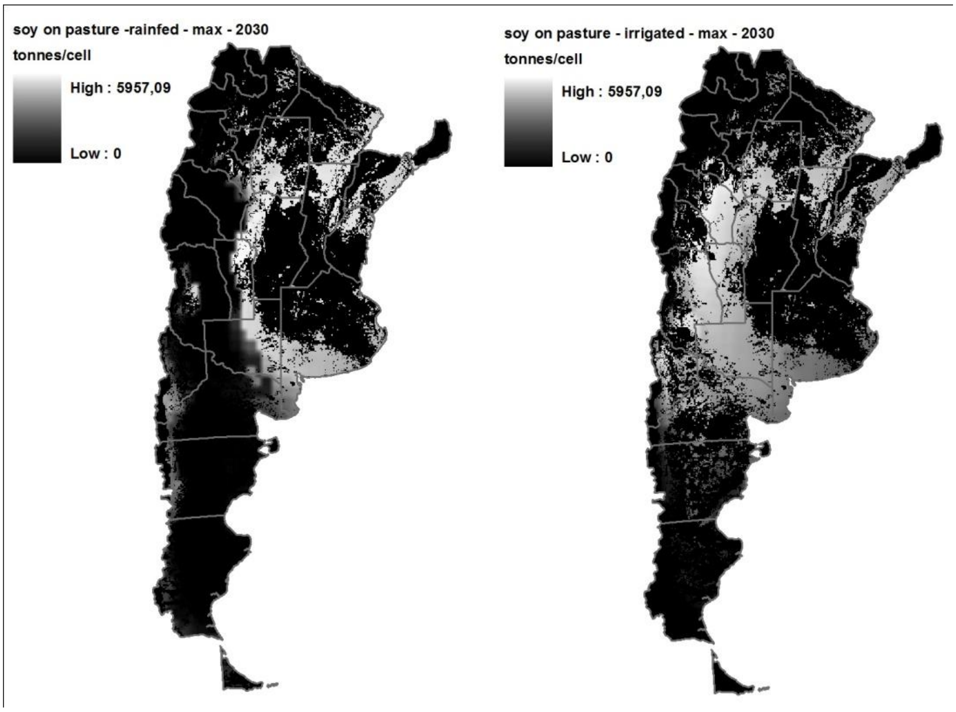


**Figure 27: Rainfed vs irrigated soy production pastures (units in tonnes/cell).**

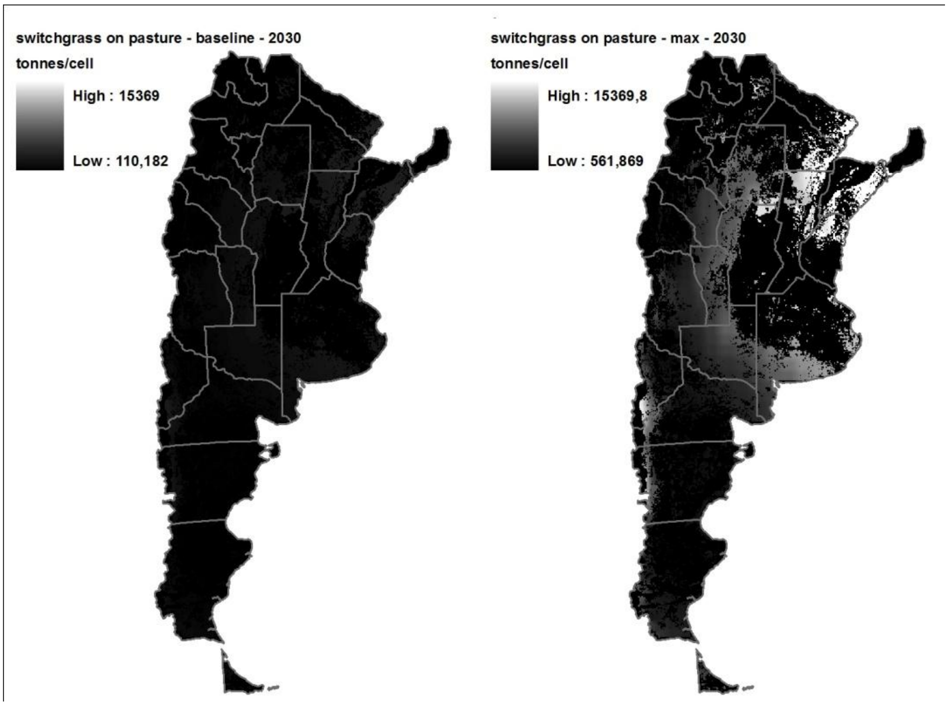


**Figure 28: The spatial effect of raising the available pasture share (In this case switchgrass baseline, no diet change vs switchgrass fully landless, no diet change. (units in tonnes/cell)**

## 4.7 Future potential

### 4.7.1 Land area

Since in the current situation all cropland is pre-occupied, the amount of cropland area available for biofuel production depends directly on yield growth. Where yield growth decreases the required area for regular crops with a proportional percentage, cropland area is released. The released area quantities in 2030 as a result of annual yield growth is shown in Table 27. No nation level parameter variation has been performed for 2015. All 2015 calculations on nation level assume 1.801 * $10^3$ hectares.

| % annual yield growth | 2030 - *1000 hectares |
|---:|---:|
| **1** | 1.687 |
| **1,33** | 4.270 |
| **1,67** | 6.605 |
| **2** | 8.694 |
| **2,333** | 10.591 |
| **2,67** | 12.309 |
| **3** | 13.871 |
| **3,333** | 15.288 |

**Table 27: Available land area for biofuel production in relation to annual yield growth rate (units in 1000* hectares/year)**

The results of Future potential are elaborated in this chapter. The fresh weight potential is a function of available land and potential yields (in kg/ha/year * 1000.

### 4.7.2 Potential in fresh weight

Table 28, Table 29 and Table 30 show the 60 scenario results in fresh matter.

| No diet change | soybean 2015 | switchgrass 2015 | soybean 2030 | switchgrass 2030 |
|---|---:|---:|---:|---:|
| **baseline, excluding pastures** | 8.987 | 17.594 | 41.263 | 82.884 |
| **baseline, including pastures** | 13.595 | 27.356 | 58.250 | 118.870 |
| **baseline, including pastures + irrigation** | 17.405 | N/A | 72.296 | N/A |
| **landless livestock, no irrigation applied** | 76.545 | 160.714 | 108.821 | 266.393 |
| **landless livestock, irrigated** | 132.407 | N/A | 199.513 | N/A |

**Table 28: fresh weight potential of scenarios, involving no diet change – per type of feedstock (tonnes*1000)**

| including change to moderate diet | soybean 2015 | switchgrass 2015 | soybean 2030 | switchgrass 2030 |
|---|---|---|---|---|
| **baseline, excluding pastures** | 8.987 | 17.594 | 41.263 | 82.884 |
| **baseline, including pastures** | 145.159 | 306.067 | 219.513 | 457.811 |
| **baseline, including pastures + irrigation** | 257.754 | N/A | 367.896 | N/A |
| **landless livestock, no irrigation applied** | 172.731 | 364.478 | 250.014 | 522.426 |
| **landless livestock, irrigated** | 308.124 | N/A | 423.617 | N/A |

**Table 29: fresh weight potential of scenarios, involving a 'moderate' diet change – per type of feedstock (tonnes*1000)**

| including change to vegan diet | soybean 2015 | switchgrass 2015 | soybean 2030 | switchgrass 2030 |
|---|---|---|---|---|
| **baseline, excluding pastures** | 8.987 | 17.594 | 41.263 | 82.884 |
| **baseline, including pastures** | 218.665 | 461.789 | 311.488 | 655.344 |
| **baseline, including pastures + irrigation** | 392.040 | N/A | 534.926 | N/A |
| **landless livestock, no irrigation applied** | 226.471 | 478.325 | 320.123 | 673.637 |
| **landless livestock, irrigated** | 406.300 | N/A | 550.701 | N/A |

**Table 30: fresh weight potential of scenarios, involving a diet change – per type of feedstock (tonnes*1000)**

### 4.7.3 Potential in energy content

The final potential of biofuel production as energy content is determined by the fresh weight potential of the various described scenarios, the energy content of the feedstock, and the feedstock conversion losses of the conversion processes. The results are described per pathway and scenario in Table 31, Table 32, Table 33.

.

| No diet change | soybean 2015 | switchgrass 2015 | soybean 2030 | switchgrass 2030 |
|---|---|---|---|---|
| **baseline, excluding pastures** | 62 | 161 | 284 | 756 |
| **baseline, including pastures** | 94 | 250 | 401 | 1.085 |
| **baseline, including pastures + irrigation** | 120 | N/A | 497 | N/A |
| **landless livestock, no irrigation applied** | 527 | 1.467 | 749 | 2.431 |
| **landless livestock, irrigated** | 911 | N/A | 1.373 | N/A |

**Table 31: final fuel potential of scenarios, involving no diet change – per type of feedstock (PJ)**

| including change to moderate diet | soybean 2015 | switchgrass 2015 | soybean 2030 | switchgrass 2030 |
|---|---|---|---|---|
| **baseline, excluding pastures** | 62 | 161 | 284 | 756 |
| **baseline, including pastures** | 999 | 2.793 | 1.519 | 4.226 |
| **baseline, including pastures + irrigation** | 1.774 | N/A | 2.540 | N/A |
| **landless livestock, no irrigation applied** | 1.189 | 3.326 | 1.729 | 4.815 |
| **landless livestock, irrigated** | 2.120 | N/A | 2.923 | N/A |

**Table 32: final fuel potential of scenarios, involving a ‘moderate’ diet change – per type of feedstock (PJ)**

| including change to vegan diet | soybean 2015 | switchgrass 2015 | soybean 2030 | switchgrass 2030 |
|---|---|---|---|---|
| **baseline, excluding pastures** | 62 | 161 | 377 | 756 |
| **baseline, including pastures** | 1.505 | 4.214 | 2.843 | 5.981 |
| **baseline, including pastures + irrigation** | 2.698 | N/A | 4.882 | N/A |
| **landless livestock, no irrigation applied** | 1.558 | 4.365 | 2.921 | 6.148 |
| **landless livestock, irrigated** | 2.796 | N/A | 5.026 | N/A |

**Table 33: final fuel potential of scenarios, involving a vegan diet change – per type of feedstock (PJ)**

As can be seen, all scenarios enable a positive. However, diet change enables a much higher biofuel potential than efficiency gains. Naturally a combination of the two developments enables an even higher potential .

### 4.7.4 CO2 emission reduction potential

CO2 emission savings are a product of the biofuel pathway carbon balance, and the fresh weight potential. Relative differences are similar to fresh weight and energy potential. Due to the combination of lower fresh weight potential and lower emission savings per unit of soybean biodiesel, this pathway has a 5-6 times lower emission saving potential than switchgrass ethanol. Developments in agricultural efficiency and dietary pattern boost the potential emission savings dramatically.

| No diet change | soybean 2015 | switchgrass 2015 | soybean 2030 | switchgrass 2030 |
|---|---|---|---|---|
| baseline, excluding pastures | 3.209 | 10.357 | 14.733 | 48.791 |
| baseline, including pastures | 4.854 | 16.104 | 20.798 | 69.975 |
| baseline, including pastures + irrigation | 6.214 | N/A | 25.813 | N/A |
| landless livestock, no irrigation applied | 27.330 | 94.607 | 38.854 | 156.818 |
| landless livestock, irrigated | 47.275 | N/A | 71.235 | N/A |

**Table 34: : CO2 equivalent emission savings, involving no diet change, compared to fossil fuel equivalent (Unit: Mtonnes/year)**

| including change to moderate diet | soybean 2015 | switchgrass 2015 | soybean 2030 | switchgrass 2030 |
|---|---|---|---|---|
| baseline, excluding pastures | 3.209 | 10.357 | 14.733 | 48.791 |
| baseline, including pastures | 51.828 | 180.173 | 78.805 | 272.582 |
| baseline, including pastures + irrigation | 92.029 | N/A | 131.784 | N/A |
| landless livestock, no irrigation applied | 61.672 | 214.557 | 89.695 | 310.619 |
| landless livestock, irrigated | 110.014 | N/A | 151.679 | N/A |

**Table 35: CO2 equivalent emission savings, involving a 'moderate' diet change, compared to fossil fuel equivalent (Unit: Mtonnes/year)**

| including change to vegan diet | soybean 2015 | switchgrass 2015 | soybean 2030 | switchgrass 2030 |
|---|---|---|---|---|
| baseline, excluding pastures | 3.209 | 10.357 | 19.540 | 48.791 |
| baseline, including pastures | 78.073 | 271.841 | 147.504 | 385.782 |
| baseline, including pastures + irrigation | 139.976 | N/A | 253.313 | N/A |

| | | | | |
|---|---|---|---|---|
| **landless livestock, no irrigation applied** | 80.860 | 281.576 | 151.594 | 396.550 |
| **landless livestock, irrigated** | 145.067 | N/A | 260.783 | N/A |

**Table 36: CO2 equivalent emission savings, involving a vegan diet change, compared to fossil fuel equivalent (Unit: Mtonnes/year)**

# 5 Conclusions

In this section, the main research question is answered by elaborating conclusions on the sub-questions. The conclusions follow the structure of the methodology.

**The main research question is the following:**

"How do spatial constraints and different methods of reallocating food and biofuel crops affect biofuel production quantities in scenarios up to 2030?"

**Sub questions**

1. What is the biofuel potential per type of land area in 2007, while disregarding biodiversity hotspots, high land slopes and areas distant to infrastructure, expressed in fresh matter, energy content and GHG emission reduction?
2. What is the 'sustainable' biofuel potential in 2015 and 2030, considering both baseline and alternative livestock farming scenarios?
3. How is this biofuel potential affected by the choice of methodology on how to allocate food and biofuel crops?

## 5.1 Geographic and land use class potential (sub-question 1)

From the geographic potential, the Sugarcane irrigated – ethanol pathway is the most potent (10.457 Mtonnes/year ; 11.521 PJ/year; 734 Mtonnes/year, as fresh matter, energy content and CO2 equivalent emission reduction respectively ). Sugarcane rainfed – ethanol (98 Mtonnes/year ; 105 PJ/year; 7 Mtonnes/year) is the utter least potent in Argentina. The potential of switchgrass ethanol (792 Mtonnes/year ; 6.654 PJ/year; 429 Mtonnes/year) is lower than that of irrigated sugarcane ethanol but does not require controversial irrigation. Because of the preference of rainfed over irrigated biofuel production, switchgrass ethanol is considered a more feasible and future oriented pathway than sugarcane ethanol. The soybean biodiesel potential is 438 Mtonnes/year; 2.438 PJ/year; 127 Mtonnes/year.

Regarding soybean diesel, the performance of final fuel potential is relatively poor, whereas the effective energy production and the GHG emission savings are very poor compared to the other biofuel pathways.

## 5.2 Future potential (sub-question 2)

Regarding the sustainability criteria, this study has focused on production potential located on former cropland and pastures. The presented scenarios are a combination of variance in population level (expressed as an asset of time), diet type, crop efficiency factor and livestock efficiency factor. The aggregated scenarios ( see Table 28 - Table 36) show that although this study has focused intensively on comparing cropland allocation methodologies, there may be much greater potential in converting pasture land into cropland.

Including pastures in the potential under baseline conditions leads to 41 – 55 % higher potential levels, depending on the biofuel type and year. Assuming a full transition to landless livestock adds another 463% ; 487% ; 87% ; 124% to the potential of 2015 soybean ; 2015 switchgrass ; 2030 soybean and 2030 switchgrass respectively.

Scenarios involving a moderate diet change under baseline conditions, including pastures, generate 11 times more potential in 2015 and 4 times in 2030. In case of a transition to fully landless livestock, a moderate diet doubles biofuel potential.

The same scenario's but then involving a vegan diet change under baseline conditions, including pastures, generate 16-17 times more potential in 2015 and 5 times in 2030. In case of a transition to fully landless livestock, a vegan diet triples biofuel potential.

## 5.3 Model comparison (sub-question 3)

The main element of additionality in this study has been the comparison of crop allocation methodologies. Although the suitability allocation model has proven its effectiveness with regard to the optimal allocation of many crops including biofuels, comparison with a simple homogeneous allocation model shows that suitability allocation is far from optimal if one crop's suitability is (by accident) just a little lower than that of other crops on most locations. Because of this, the allocation of cereals (the largest crop group) is poor, thereby largely nullifying the net effectiveness of the model. Small differences in suitability input data can thus lead to large displacement in crop distribution. As in this case cereals account for the largest share of cropland in comparison to the other crops, the actual land use efficiency of all crops combined (using homogeneous allocation) is only 2,5% lower than while using best suitability to allocate land. The main reason for this issue is large similarity in suitability data while using 'all or nothing' allocation rules. With neither biofuel using the cereal suitability dataset, future biofuel potential levels are likely considered to be overestimated. However, with growing crop yield levels the share of cereals in land area decreases along with the overestimation of biofuel potential. In Figure 18 it is visualized how increasing biofuel production area due to yield growth forces biofuel production on less suitable terrain, thereby decreasing average yield levels.

# 6 Discussion

In  the discussion, it is analyzed how the methodology and its data sources induce uncertainty, and how this can affect the results. This is done in individual paragraphs that discuss both methodological stages and individual parameters. Finally,  a paragraph is dedicated to the consequences of not including carbon emissions from land conversion in the model.

## 6.1 Uncertainty induced by land use classification

It was initially aimed to actively use land cover classification data in allocation processes. However due to the poor quality of Globcover's mosaic classification labeling, it has only been used as a shape mask to identify the regions on which rule based allocation can consecutively be applied.  A land use classification system with more detailed labeling might be able to identify area of land that does not need to be excluded, land area that is now 'hidden' under a crude mosaic label, in spite of the 300 meter resolution of Globcover. In case the use of mosaic classes is required, improvements could be made by using fixed fractions of vegetation instead of crude ranges.

## 6.2 Data quality of yield performance

The data of feedstock yield performance is withdrawn from different quality of sources. Since especially soybean cultivation is abundant in Argentina, high quality data considering yield is available. Due to the high availability of empirical yield data, uncertainty of soybean yield is very low. Sugarcane is also grown in Argentina, but to a lesser extent. As there is much less empirical data to validate the IMAGE potential productivity data, the uncertainty of sugarcane yield is a bit higher. Regarding switchgrass, the uncertainty is very high as there is no empirical data available, and the global reports of switchgrass yield vary greatly. A 5-12 tonnes/ha range has been used in combination with the IMAGE "precipitation based grasses database". This is a crude and debatable proxy. The results of final potential are all directly dependent on yield, which is why the conclusions may be different while using a different assumption for yield.

The suitability datasets used from FGGD/GAEZ inventory cover only a part of northern Argentina and therefore had to be extended with IMAGE data. The datasets show similar suitability on many locations, which leads to the question on whether suitability is a good criteria for allocation.

## 6.3 Required crop area

The type of crops harvested in Argentina and area quantities have historically varied and still vary each year. The assumption of keeping the demand for crop constant with regard to variety of demand is one of the crude assumptions that were required to start spatial modeling.

## 6.4 Modeling effects

As previously stated, the models that have been used are simple. The allocation rules that have been used have proved effective for biofuel allocation, but also biased with regard to cereal crops. Naturally it is possible to build increasingly advanced models with softer allocation rules, and thereby approach reality. Economic and social factors could be involved. These are all elements that could be researched in future research. But it should be noted that any model, no matter how complex will have to cope with future uncertainty. Due to its simplicity, this model only had to deal with the relatively straightforward future uncertainties of population growth and yield efficiency increase. Making the model more complex requires many more uncertain assumptions, especially with regard to economics. This is a risk that needs to be evaluated if a modeling research is preferred over other methods.

## 6.5 Reforming the livestock sector

Future scenario results (although not modeled in detail) have shown that a much larger biofuel potential can be withdrawn by reformation of the livestock sector or diet change, than to only depend on increases in crop yield. This is very relevant information from both the perspective of science and policy. More detailed modeling to evaluate the spatial effects of changes in the Argentinean livestock sector is the most essential element lacking in this study and is thus open for further research.

## 6.6 Pathway analysis

It has been attempted to use the same data source as much as possible for the different feedstock types in order to maintain consistency in assumptions. Most of the pathway calculations are withdrawn from the JRC well to wheel program. Transport distances have been adopted from INTA to resemble application on Argentina. As the JRC study has not reviewed a switchgrass ethanol pathway, other literature has been used to calculate this pathway. Lack of empirical data with regard to switchgrass and ongoing developments with regard to this technology make the pathway analysis of switchgrass ethanol more uncertain than of the other two pathways.

## 6.7 Policy implications of the results

The results have clearly shown the energy content and GHG emissions savings of soybean diesel potential to be much lower than that of switchgrass ethanol. Yet, the biofuel promotion program of Argentina is fully aimed at the promotion of soybean biodiesel and not at second generation fuels such as switchgrass ethanol. This study has evaluated biofuels from the perspective of mitigating carbon emissions. However, in political decision making other stakes may be involved. The role that soybean production has in animal feed manufacturing and food production illustrates one of the advantages soybean diesel promotion can have in comparison to the promotion of switch grass ethanol. Policy makers should therefore interpret the results of this study within a larger context, in which mitigation of greenhouse gasses is one of many policy goals that are weighed in decision making. This applies even more strongly to the decision on whether to promote diet change. The controversy of changing diet should be weighed against the benefits that it has for biofuel production or food security. Conversely, intensification of livestock sector would increase the demand for feed and thereby soy as a main supplier.

## 6.8 Land conversion

The carbon balance of the pathways in this study, and thereafter the results of GHG emission mitigation potential does not include a very important aspect: land conversion processes. Since new biofuel production sites involve a transition from the carbon stock of the old land function to carbon stock of cultivation land, emissions from the loss of carbon stock may arise. These emissions may be high (depending on the old land use function) and may thereby nullify (a part of) the achieved GHG emission mitigation, or even negative mitigation over the lifespan of biofuel harvest. According to the EU Directive 2009/28/EC (THE EUROPEAN PARLIAMENT

AND OF THE COUNCIL, 2009) , which is still in the stage of proposal, GHG emission savings should be at least 35% now, and 50% from January 2017 onwards. The “2006 IPCC Guidelines for National Greenhouse Gas Inventories – volume 4 – chapter 5 (cropland) (Lasco et al., 2006)” provides an extensive methodology to assess carbon stocks on above and underground level in forests, cropland and other types of land use. This method can be used to determine the land conversion emissions from biofuel production increase. Due to the complexity of the method versus time limitation, it has been decided not to model the emissions from land use change. However it should still be noted that carbon losses are likely to further lower emission savings and may thereby be a decisive aspect in drawing conclusions. This is therefore a suggestion for further research.

Without accounting for carbon stock losses, it can be observed that relative emission savings of soybean diesel are a mere 37%, which is already the minimum required level according to the EU Directive 2009/28/EC. Any carbon stock losses from land conversion considering this pathway can further reduce emission savings. From this perspective, emission savings from additional soybean diesel production may be unfeasibly low. Since emission savings of the other pathways are much higher, the subjectiveness of feasibility to land conversion emissions is lower.

Although this study does not account for land conversion related carbon emissions explicitly, it is attempted to implicitly minimize this by excluding potentially high carbon stock land use classes of Globcover e.g. forests and protected areas. Whether emissions are actually minimized with this precautionary principle depends on the quality of Globcover land use classification , which has been previously considered as debatable. It should also be noted that this regards above ground carbon stock and not underground carbon stock. Peatlands are included in the list of Wdpa protected areas and are thereby accounted for. However, sites with high underground carbon stock that are not covered by this label are not accounted for. A full evaluation of carbon stock on above and underground levels can be calculated using the earlier mentioned IPCC methodology.

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# 8 Appendix

## 8.1 Land use classification

As the Globcover classification system comes with a very large number of classes, similar classes are merged into new group classes to create a set of classification that better matches the purpose of excluding 'unsuitable' land types for biofuel production. The reformed classes are the following:

- Cropland (class 14, 20, 21, 22)
- Shrubland (class 120, 130, 131, 134, 140)
- Forests (class 30, 40, 41, 42, 50, 60, 100, 101, 110)
- Sparse vegetation land  (150, 151)
- Grassland (class 141, 143 – This class does not report presence in Argentina)
- Flooded land (class 160, 161, 170, 180, 181, 185)
- Urban area (class 190)
- Bare areas (class 200,201,203)
- Water bodies (class 210)
- Permanent snow and ice (class 220)

A visualization of these classes' spatial distribution in shown in Figure 29.

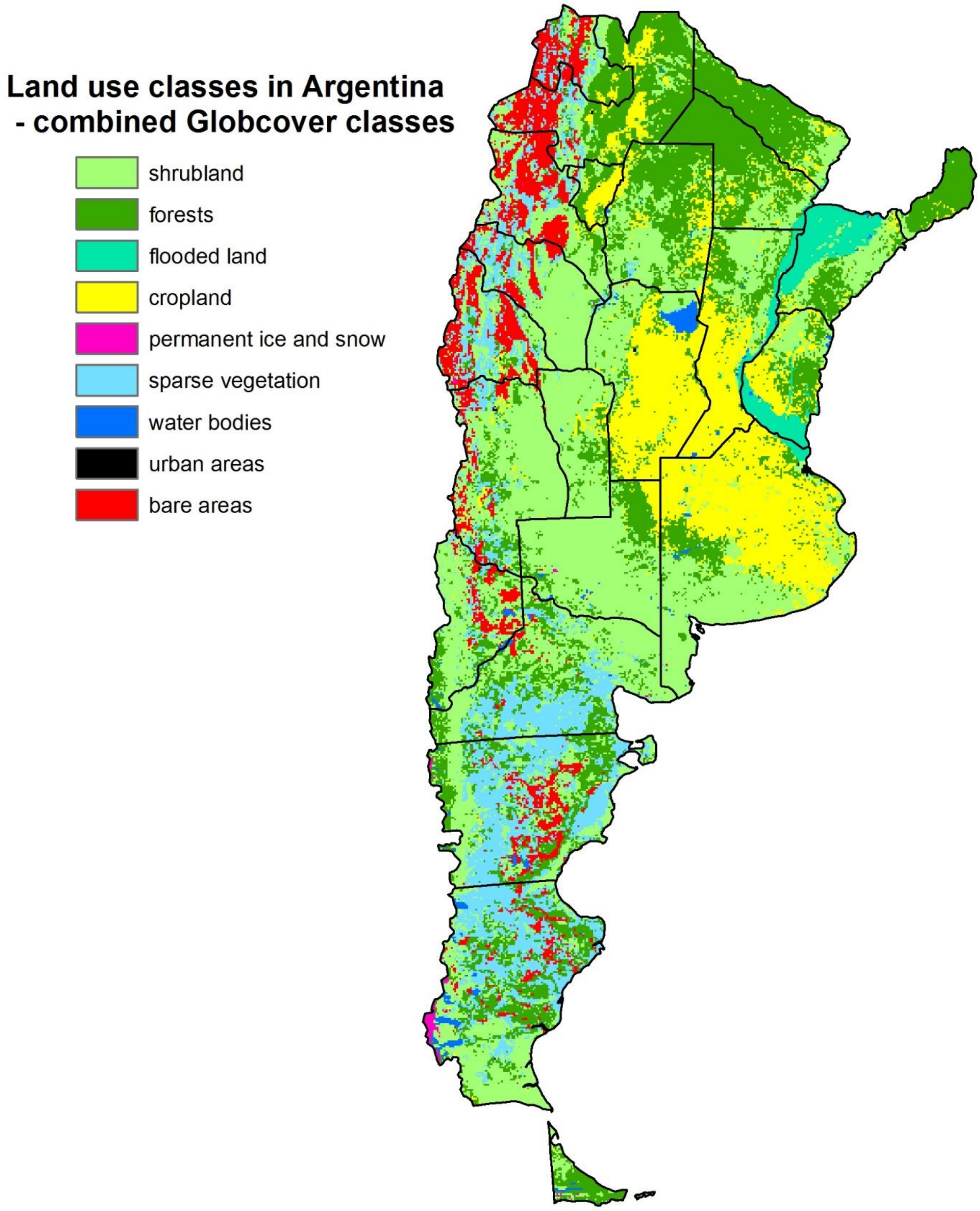


**Figure 29: Land use classes in Argentina (Globcover)**

## 8.2 Distance to main roads

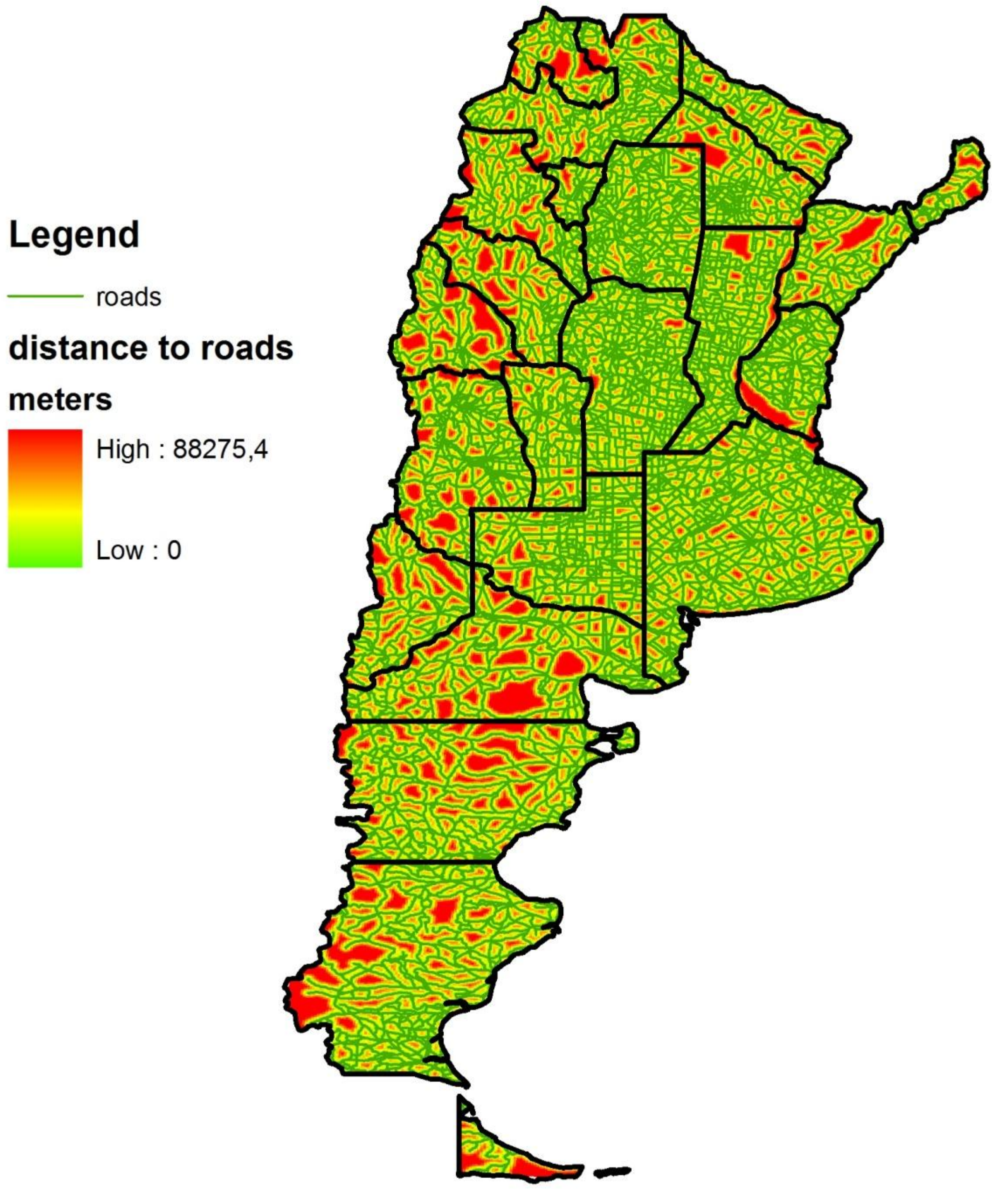


**Figure 30: Distance to roads (as spatial infrastructure constraint)**

## 8.3 Identification of pasture land

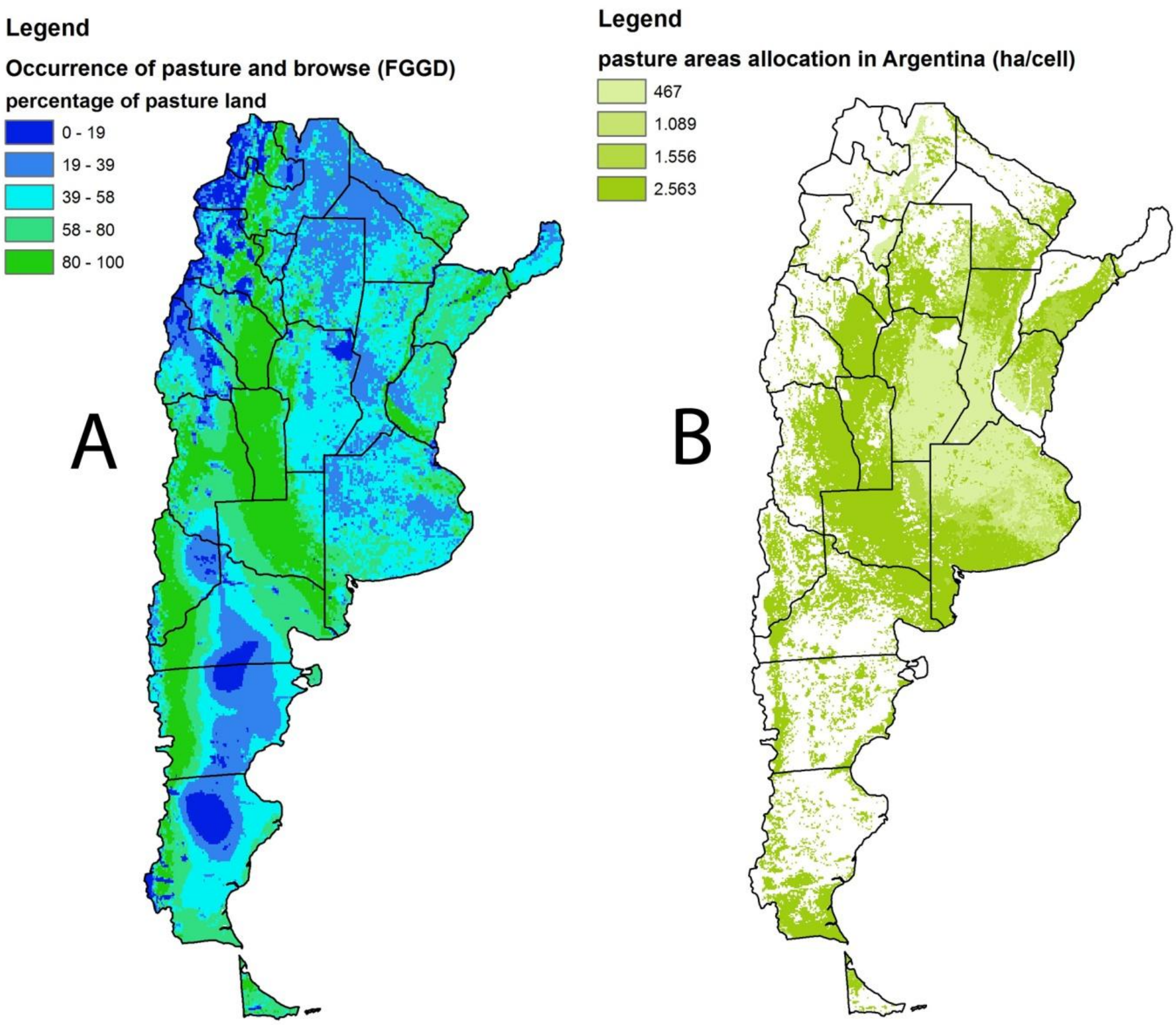


**Figure 31: Identifying pastures, using FGGD and Globcover data**

## 8.4 Background

### 8.4.1 Tools

#### *8.4.1.1 Spatial modeling and calculation tools*

ArcGIS has been used in combination with the Spatial Analyst extension to evaluate spatial input data and to perform calculations while combining various input data of (spatially explicit) sources. Python scripting has been used for building and running models, while MS excel has been used for non-spatial modeling,

#### *8.4.1.2 GIS Coordination system and projection*

All the input datasets are given in degrees latitude by longitude as a unit and use the WGS 1984 (World Geodetic System) geographic coordination system. As there is a need to calculate surface areas in metric units, the datasets have been projected, using the 20S (Southern hemisphere) datum of the UTM (Universal Transverse Mercator) projection system, which overlaps Argentina approximately at the center. UTM is a transverse cylindrical projection of the WGS 1984 sphere. While a normal Mercator Projection suffers large distortion at the poles (the far end of the longitude axis), a Transverse Mercator projection is accurate within the UTM zone and distorts more when going more east or west from the UTM zone. The latter is very well suited for the projection of Argentina, since this country stretches long from north to south, rather than from west to east. Also, Argentina is located close to the South Pole, which would cause large distortions, especially in the southern part, when using a normal Mercator projection. However, even though Argentina does not stretch as much from west to east as it does from north to south, it still covers multiple UTM zones (19S, 20S and 21S). The most central zone (20S) has been selected because the regions with the most agriculture (predominantly within northern Argentina) lie for the largest part in this zone. However, it should be noted that the coverage of 3 UTM zones causes some error in the cell surface of locations within the 19$^{th}$ and 21$^{st}$ zone.

#### *8.4.1.3 The Globcover land use classification database*

To identify land uses in Argentina, a number of global spatially explicit land use classification databases are available, e.g. Globcover of ESA, the Global Land Cover Characterization database (GLCC) from USGS, Boston University's Global Land Cover Dataset BU-MODI) and IIASA's GLC2000 – of which Globcover is the successor. Globcover has been selected because it is the most recent data available and it also provides a high 300 meter resolution. However, also this database has some shortcomings . These shortcomings are inherent to the methodology of using satellite reflection image data in combination with an algorithm. In spite of random validation, there is no guarantee that the correct land use class is identified. The other major shortcoming is that this database uses mosaic classes that may feature multiple types of land use, but only mention the most dominant functions. Proportions between different functions are indicated by crude share ranges. An example from the Globcover legend to illustrate this is the following: "Closed to open (>15%) (broadleaved or needleleaved, evergreen or deciduous) shrubland (<5m)". This description lacks information on other land use types than the small fraction of (broadleaved or needleleaved, evergreen or deciduous) shrubland (<5m) that is mentioned.

The Globcover land utilization class database reflects the dominant type of land use within a grid cell. It is based on reflectance measurements of the MERIS medium resolution spectrometer of the ENVISAT satellite and delivers a 300 meter resolution output. Its classification method is based on the FAO LCCS land use typologies and is also designed to be compatible with the GLC2000 classification. The Globcover satellite images were taken between 1 December 2004 and 30 June 2006. The version that has been used (version 2.2) has been validated by regional experts. For Argentina, the data has been validated by Instituto Nacional de Tecnología Agropecuaria – Argentina (INTA) (Bicheron P. (Medias-France) et al., 2008).

The data may fail to identify for example forests in cropland mosaic classes, especially in cases where the forest takes a minor share of the grid cell. Because of this, some parts of the cropland classified land may actually be forests, and that is a problem, since forests are not allowed to be converted to croplands. This issue is further elaborated on in the discussion of this report.

### 8.4.2 Productivity data sources

#### *8.4.2.1 IMAGE productivity database*

The potential productivity database is one of the results from the IMAGE model of the Netherlands Environmental Assessment Agency. The methodology of the model, such as described by the Netherlands Environmental Assessment Agency is the following:

At first, the FAO AgroEcological Zones approach is used to determine how crops are potentially distributed. If the length of the growing season appears to be adequate for sufficient crop growth performance, a model using photosynthesis/respiration (Alcamo et al., 1998)(Leemans, 1994)**)** is used to determine the productivity of the crop type. This concerns a constraint free, rainfed crop yield.

Subsequently, a 'soil reduction factor' (with a range from 0.1 to 1.0) is used to account for soil conditions in the constraint-free, rainfed crop yield. The soil reduction factor is based on the methodology which is defined by *the land evaluation computer system (LECS)* (Wood & Dent, 1983) using the *FAO soil map of the world* (FAO, 1991). The crop productivity that results from this methodology is called *reduced potential productivity of crops*.

While in case of regular crops it is aimed to optimize the yield of edible parts, the priority in biofuel crop productivity lies in the optimization of energy content. Therefore, the crop growth model has been run again with changed parameters to account for the productivity of energy crops. The 'energy crops' concern sugarcane, maize, and woody species.

The results are published in a spatial resolution of 0,5 degree, which is substantially less accurate than the resolution of the other databases that are used.

#### *8.4.2.2 MapSPAM spatial production allocation*

MapSPAM (You et al., 2010) is an intermediate level, spatially explicit crop production database. The production statistics originate from national and sub-national (tabular) agricultural statistics, either as an integrated part of agroMAPS (which is one of the mapSPAM input variables) or in addition to agroMAPS. These additional statistical data include sources such as World Food Programme (WFP) crop and food supply assessment mission surveys, agricultural performance surveys, national bureaus of statistics, regional agricultural centers, ministries of agriculture, rural and extension services, regional NGOs, agricultural censuses, ministries of the environment, and water resource groups. The production data from statistics are spatially allocated using a 'Cross-entropy method'. This method uses the following variables in the allocation process: land use [including various databases: BU-MODIS Land Cover, and JRC's GLC2000 for the year 2000 and one for 1992/93 (USGS's GLCC], irrigated areas (Global Map of Irrigated Areas (GMIA)), crop suitability classes (AEZ), and population density .

The spatial resolution of the mapSPAM database is in 5 minute latitude by longitude (which is equivalent to 10 km at the equator).

#### *8.4.2.3 Productivity statistics*

The Argentinean ministry of agriculture has an extensive database (Ministerio de Agricultura Granaderia y Pesca, ) of the amount of (harvested) area, yields and production quantities of all major crops that are currently produced or that have been produced in Argentina. All data is available per province. It is considered per type of crop (which will in this case be biofuel feedstock) whether this data is of value to calibrate the spatially explicit data of the IMAGE potential productivity database or spatially explicit current production levels from MapSPAM. Calibration is done by setting the spatially explicit data equal to statistic levels, individually per province.

### 8.4.3 Background of biofuel pathways

#### *8.4.3.1 Soybean crop characteristics*

Soybeans are an annual summer crop that takes 75 to 80 days to mature, while growing about 1 meter high. It is the most abundantly harvested crop in Argentina, with a production of approximately 89 million tonnes of soybean (FAOSTAT 2007), that produces both vegetable oil and soybean cake as raw products. The seeds grow in hairy pods in clusters of 3 to 5, and are the only part of the plant that is harvested. The leaves fall of once the seeds are matured. As a legume type of plant, this crop fixes nitrogen and can be used in crop rotation as a soil nitrogen replacer. The far majority of the soybean crops in Argentina are genetically engineered to resist glyphosate (the Roundup® weed killer) and enable zero tillage cultivation. Harvest is performed by machines.

Soybeans as a single crop even account for 51 % of the total agricultural area (Systema Integrado de Información Argropecuaria). The oil that can be withdrawn from soybean production is a potential feedstock for biodiesel . The ratification of a biofuel law in 2006, which set a mandatory blending requirement of 5% in 2010 is set to speed up the production development of biodiesel in Argentina (Regimen de Regulacion y Promocion para la Produccion y Uso Sustentables de Biocombustibles, Law no. 26.093/06; SAGPyA,2006). Also, a reduction in export tax of soybean biodiesel stimulates Argentinean biodiesel production. Due to these measures, 200 million liters of biodiesel have been produced in 2007, and have been projected to increase to exceed 2 billion in 2010 (USDA). From the total soybean production (46 million tonnes), around 12 million tonnes are exported as raw soybeans, 26 million as soybean cake and 6 million as soybean oil (FAOSTAT 2007). This means that nearly all soy products are exported. Also, Argentina imported 2,2 million tonnes of soybeans in 2007.

Soybeans have multiple functions as it is used as biofuel feedstock (arising from the 18,8 % oil content of the soybean), as a resource for animal feed and as a resource for the food industry. The soybean cake is a mixture of proteins, carbohydrates, water and some remaining oil. Although this could also qualify as biofuel feedstock, it is currently not applied as such. Soybean cake is a high quality resource for animal feed production due to its high protein content, and has a competitive economic value as such. Also the oil can be used for food production and non-food purposes.

#### *8.4.3.2 Sugarcane crop characteristics*

Sugarcane is a tall perennial grass that is best suited to grow in warm temperate to tropical climates. It has a high moisture content of around 70% and requires large amounts of water to grow. The rest of the plant consists of (dissolved) sugar, bagasse, stalk and leaves. It is produced in a quantity of around 30 million tonnes in Argentina according to FAO estimates (REF). However, it should be noted that national statistics from the ministry of agriculture report a production of around 19 million tonnes on a harvested area of 229 thousand ha. This amounts to only 0.8% of the total harvested cropland due to the high yields of sugarcane production compared to types of crops. Harvest of sugarcane involves the requirement of either abundant rainfall or irrigation. Currently, there is no commercial interest for bio-ethanol production in Argentina for petrol blending. This has mainly been due to the artificially low petrol prices and the increase in the price of sugar(Lamers et al., 2008). So far, ethanol production is aimed at food, beverage and the pharmaceutical industry (SAGPyA & IICA, 2005, p. 11)

#### *8.4.3.3 Switchgrass crop characteristics*

Switchgrass is a perennial warm season grass that uses C4 carbon fixation, originally native to North America. It has yields reported of between 5 and 12 tonnes/ha in Argentina (INTA). Switchgrass is currently not reported to be commercially grown for biofuel production or other purposes in Argentina. As a second generation lignocellulosic feedstock type, it can be converted into biofuel liquids through gasification and subsequent Fischer Tropsch synthesis, or through hydrolysis and fermentation.

### 8.4.4 The production pathway of soybean diesel

Following the harvest of soybeans, the beans are transported to a processing and conversion plant by truck. The transport is assumed to concern a 300 km distance of raw bean transport by truck to the decentral location of the processing plant (Muzio et al., 2008) (at the harbor), after which the final fuel can then enter the national or export market. This transport distance is adopted from INTA in replacement of the 700 km distance of the JRC study, which applies to soybean production in Brazil. Input values during cultivation have been adopted from the Secretariat of Agriculture, Feedstock, Fishing and Food (SAGPyA).

In the conversion plant the oil fraction is extracted from the beans, using hexane solvent (producing both vegetable oil and soybean cake). After some refining processes of the vegetable oil, it enters the process of esterification, using various chemicals and energy as input. Glycerine is produced as a waste product, but is a useful chemical that can replace propylene glycol. Carbon credits for its avoided emissions are subtracted as a credit. The final output is a fuel called FAME (Fatty Acid Methyl Esters), which is commonly known as biodiesel.

For soybeans, the production pathway is assumed the following:

Cultivation and harvest
Transport by truck (300 km, raw soy beans)
Extraction of vegetable oil at decentral location
Refining of vegetable oil
Esterification

### 8.4.5 The production pathway of sugarcane production

The transport is assumed to firstly concern a 20 km distance of raw sugarcane transport by truck to the local processing plant (JRC), after which the ethanol is then transported to a decentralized location on which it enters the market (national or export). The transport of ethanol to the decentralized location is assumed to regard a 300km transport by truck. This is taken analogous to the transport of soybeans to ensure that the final fuels are made available at a similar decentralized location.

The processing of sugarcane can deliver either sugar or ethanol, in combination with some by-products e.g. molasses (in case of sugar as the main product), vinasse, bagasse, and stalks. Vinasse is produced from the fermentation of molasses and is fed back to the cultivation site as a fertilizer by means of spraying the vinasse over the land with water cannons. Bagasse is used to generate the heat that is required to distillate the sugar in the sugar mill. In contrast to the products from soybeans, one has to choose whether to produce sugar or ethanol from sugarcane. Since sugar has its own economic value, this choice will be largely influenced by the market value of sugarcane and ethanol. Since bagasse is used to to fuel the energy demand of sugarcane conversion, little external energy inputs are needed. As the sugarmill and conversion processes gradually become more efficient, energy from excess bagasse can be used for other purposes. Today, sugar mills use about 90% of the bagasse produced for its own consumption, but this may decrease to 70% if the steam engine (which is used to power the sugar mill, using bagasse) becomes more efficient (COOPERATIVA_CENTRAL_DOS_PRODUTORES_DE_AÇÚCAR_DO_ESTADO_DE_SÃO_PAULO., 1989)(Muzio et al., 2008). Carbon credits are awarded to account for the emission savings from excess bagasse production.

For sugarcane, the production pathway is assumed the following:

Cultivation and harvest
Vinasse transport
Transport of the sugarcane to the sugar mill by truck (20 km, raw sugarcane)
Sugarcane to ethanol conversion
Transport by truck to decentralized location (300 km, ethanol)

### 8.4.6 The production pathway of switchgrass ethanol

The transport is assumed to firstly concern a 50 km distance of raw switchgrass transport by truck to the local processing plant (JRC - straw), after which the ethanol is then transported to a decentralized location on which it enters the market (national or export). The transport of ethanol to the decentralized location is assumed to regard a 300km transport by truck. This is taken analogous to the transport of soybeans and sugarcane to ensure that the final fuels are made available at a similar decentralized location.

The production of bio-ethanol is split in two stages, hydrolysis and fermentation. Although bio-ethanol can most easily be produced from sugars (extracted from sugar crops) and a bit less easily from starch crops, the total yields are quite low, since the most prevalent forms of hydrocarbons in crops are cellulose, hemi cellulose, and lignin (which is not a sugar) (Lin & Tanaka, 2006) (this composition is also called 'lignocellulosic').

Since this technology leaves more opportunities for improvement in the coming decades up to 2030, this biofuel conversion technology is preferred over Fischer-Tropsch synthesis. Conversion efficiency data is withdrawn from JRC (bio-ethanol production from wheat-straw).

For switchgrass, the production pathway is assumed the following:

Cultivation and harvest
Transport of switchgrass by truck (50 km, raw switchgrass)
Hydrolysis and fermentation conversion
Transport of ethanol by truck (300 km, ethanol)

### 8.4.7 The inefficiency of large scale lacto-ovo-vegetarianism

It is highly complex to allocate land use to a particular type of diet. Feed crops may be allocated to any kind of livestock product, as there are no statistics available that relate to specific types of livestock to the consumption of feed crops. Likewise, pasture land can be allocated to any ruminant cattle product (beef, milk, wool). Another issue is the overlap in resource allocation of livestock products. The livestock industry is a complex and balanced system that is characterized by interdependencies and overlap. For example, dairy products and meat may involve the same cattle. This raises difficulties with the land use allocation if all Argentineans would follow a lacto-ovo-vegetarian diet (which rejects meat, but does demand dairy products and eggs). The livestock industry is bound to the rules of the animal reproduction system, which implies that for each dairy cow, a bull that cannot produce milk is born. While these bulls are now used for meat production, these animals would become useless if all people would switch to a lacto-ovo vegetarian diet. Also dairy cows that are no longer productive are used for meat production in the regular livestock industry.

Removing the meat production from the system causes inevitable efficiency losses which are characterized by an increased waste flow of killed animals that no longer benefit food production. From an ethical perspective, this would actually be worse than a regular diet, because in this case animals are killed without purpose. Due to overlap of production systems and the inevitability of the for vegetarians useless birth of male calves, the savings of land use from a nationally applied vegetarian diet would be lower than as indicated by existing studies that estimate vegetarian 'footprint' indicators within the existing paradigm of a mixed livestock industry. In the latter case a vegetarian diet can be very effective because the land and resource use of the unused male animals is allocated to meat production. Naturally, this assumption does not hold when vegetarianism is applied to an entire population. Hence, a completely vegetarian livestock sector is thereby inherently more inefficient than a mixed one. It is therefore considered that it would not only be complex to model the land use impact of an altered livestock system, it is also unrealistic and undesirable from an environmental and ethical point of view.