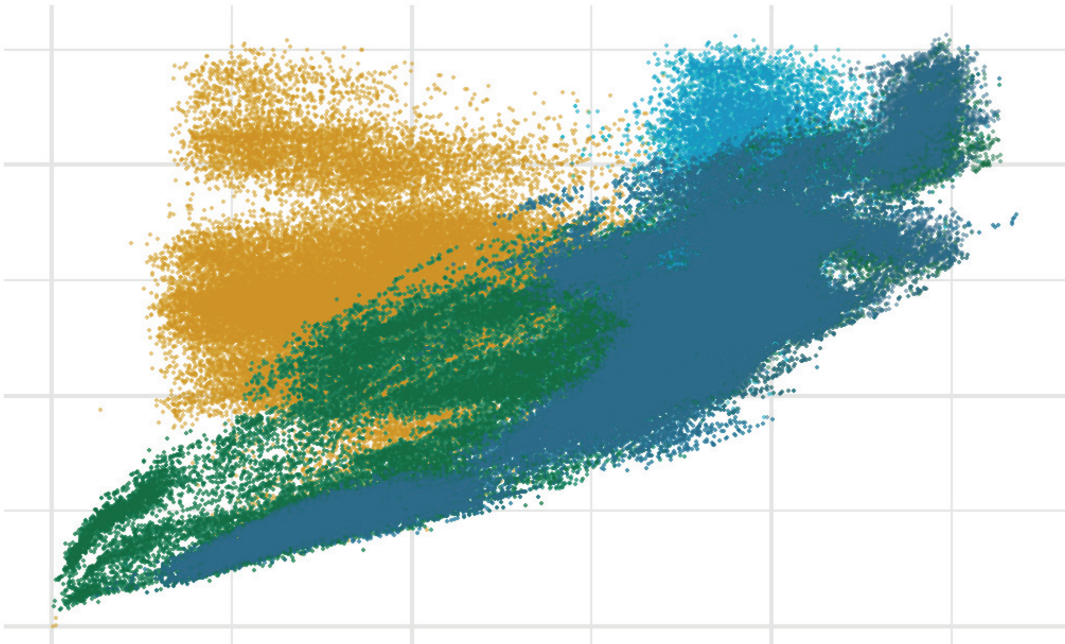
Max-Planck-Institut
für Meteorologie

MAX PLANCK
GESELLSCHAFT

International Max Planck Research School
on Earth System Modelling

On the interactions between land and water use in Brazilian rainfed agriculture



Rafaela Ariana Flach

Hamburg 2020

Berichte zur Erdsystemforschung
Reports on Earth System Science

232
2020

Hinweis

Die Berichte zur Erdsystemforschung werden vom Max-Planck-Institut für Meteorologie in Hamburg in unregelmäßiger Abfolge herausgegeben.

Sie enthalten wissenschaftliche und technische Beiträge, inklusive Dissertationen.

Die Beiträge geben nicht notwendigerweise die Auffassung des Instituts wieder.

Die "Berichte zur Erdsystemforschung" führen die vorherigen Reihen "Reports" und "Examensarbeiten" weiter.

Notice

The Reports on Earth System Science are published by the Max Planck Institute for Meteorology in Hamburg. They appear in irregular intervals.

They contain scientific and technical contributions, including Ph. D. theses.

The Reports do not necessarily reflect the opinion of the Institute.

The "Reports on Earth System Science" continue the former "Reports" and "Examensarbeiten" of the Max Planck Institute.

Anschrift / Address

Max-Planck-Institut für Meteorologie
Bundesstrasse 53
20146 Hamburg
Deutschland

Tel./Phone: +49 (0)40 4 11 73 - 0
Fax: +49 (0)40 4 11 73 - 298

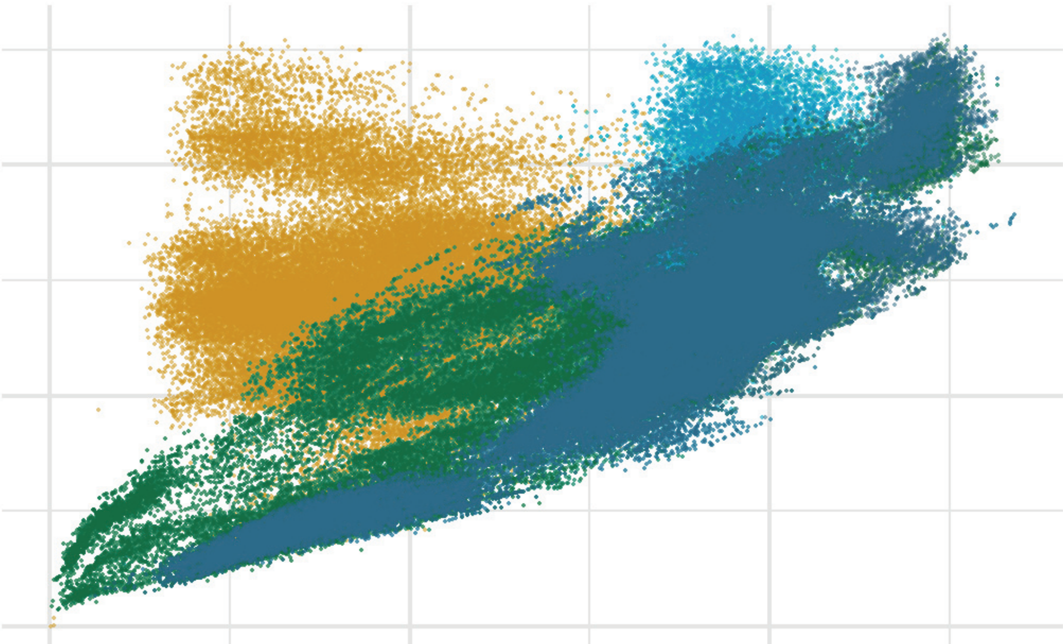
name.surname@mpimet.mpg.de
www.mpimet.mpg.de

Layout

Bettina Diallo and Norbert P. Noreiks
Communication

Copyright

On the interactions between land and water use in Brazilian rainfed agriculture



Rafaela Ariana Flach

Hamburg 2020

Rafaela Ariana Flach
aus Francisco Beltrão, Brasilien

Max-Planck-Institut für Meteorologie
The International Max Planck Research School on Earth System Modelling
(IMPRS-ESM)
Bundesstrasse 53
20146 Hamburg

Universität Hamburg
Geowissenschaften
Meteorologisches Institut
Bundesstr. 55
20146 Hamburg

Tag der Disputation: 24. Januar 2020

Folgende Gutachter empfehlen die Annahme der Dissertation:
Prof. Dr. Uwe Schneider
Dr. Kerstin Jantke

Vorsitzender des Promotionsausschusses:
Prof. Dr. Dirk Gajewski

Dekan der MIN-Fakultät:
Prof. Dr. Heinrich Graener

The figure on the front page presents an abstract figure I made when analyzing the relationships between crop yields and water use for all of my simulation units.

Berichte zur Erdsystemforschung / Max-Planck-Institut für Meteorologie 232
Reports on Earth System Science / Max Planck Institute for Meteorology 2020

ISSN 1614-1199

ABSTRACT

In the coming decades, one of humankind's main challenges will be to guarantee food supply for a growing population while managing ever more scarce resources, and safeguarding the availability of water and land for natural ecosystems. Brazil is a country with abundance of water and land resources, and has recently become one of the world's main exporters of agricultural commodities. The Brazilian agricultural sector recently went through unprecedented intensification and extensification processes, which include the expansion of cropland and pasture areas into vulnerable ecosystems.

This PhD thesis advances the research field on water and land resources assessment by investigating the following processes: i) changes in green water use by major rainfed crops in Brazil during recent decades ii) potential improvements of land and green water productivity for Brazilian rainfed crops, with and without implementation of supplemental irrigation, iii) influences of intensification and expansion of soybean production in Brazil on green water use, and iv) impacts of double-cropping on water use intensity.

The process-based biogeophysical crop model EPIC was chosen and applied to simulate water use and crop growth for Brazilian rainfed crops, under diverse management conditions. In Chapter 2, I simulated yields, water use and water productivity for soybeans, maize, cotton and wheat under different scenarios of agricultural management, for rainfed and irrigated conditions. Chapter 3 focuses on soybean and maize, and analyzes water use for the production of these crops under single and double-cropping conditions.

The results show an increase in green water use for the production of maize, cotton, soybeans and wheat from 145 to 263 km^3 per year between 1990 and 2013. This increase is in large part due to the expansion of harvested area for soybean production. The analysis of management scenarios shows that improving nutrient management has a larger potential to improve land and water productivity compared to supplemental irrigation. Furthermore, supplemental irrigation would lead to a reduction in water productivity despite marginal improvements in land productivity. The analysis of double-cropping practices for soybean and maize production systems finds a greater water appropriation of these systems avoiding cropland expansion and improving overall water productivity.

This thesis improves the understanding of current and future use of land and water, the role of intensification and expansion processes, and interactions between land and water use. The results lead to the main conclusion that harvested area expansion has been a major driving force in the increase of green water appropriation in Brazil in the last decades, but that different intensification processes have led to a more productive use of water and land over time. More importantly, the growth of double-cropping has allowed a decoupling between the appropriation of water and land, allowing a great increase of agricultural water use without further expansion of cropland.

ZUSAMMENFASSUNG

Eine der größten Herausforderungen der Menschheit in den kommenden Jahrzehnten wird es sein, die Nahrungsversorgung einer wachsenden Bevölkerung zu gewährleisten, gleichzeitig immer knapper werdende Ressourcen zu bewirtschaften und weiterhin Wasser und Land für natürliche Ökosysteme zu erhalten. Brasilien ist ein Land mit reichen Wasser- und Bodenressourcen und hat sich in jüngster Zeit zu einem der weltweit größten Exporteure von Agrarerzeugnissen entwickelt. Der brasilianische Agrarsektor durchlief in jüngster Zeit beispiellose Intensivierungs- und Ausweitungsprozesse, zu denen auch die Ausweitung von Ackerland und Weideflächen in empfindlichen Ökosystemen gehörte.

Die vorliegende Dissertation führt das Forschungsfeld der Modellierung von Wasser und Bodenressourcen weiter, indem sie folgende Prozesse untersucht: i) Änderungen der Nutzung von grünem Wasser durch brasilianischen Regenfeldbau in den letzten Jahrzehnten, ii) potentielle Verbesserungen der Land- und Grünwasserproduktivität für den brasilianischen Regenfeldbau, mit und ohne Durchführung einer zusätzlichen Bewässerung, iii) Einflüsse von Intensivierung und Ausweitung der Sojaproduktion in Brasilien auf die Nutzung von grünem Wasser und iv) die Auswirkungen einer zweimaligen Feldbestellung auf den Wasserfußabdruck.

Das prozessbasierte biogeophysikalische Pflanzenmodell EPIC wurde ausgewählt und angewendet, um den Wasserverbrauch und das Pflanzenwachstum für brasilianischen Regenfeldbau unter verschiedenen Managementbedingungen zu simulieren. In Kapitel 2 werden Erträge, Wasserverbrauch und Wasserproduktivität für Sojabohnen, Mais, Baumwolle und Weizen unter verschiedenen Szenarien der landwirtschaftlichen Bewirtschaftung und unter unterschiedlichen Regen- und Bewässerungsbedingungen modelliert. Kapitel 3 konzentriert sich auf Anbau von Soja und Mais und analysiert den unterschiedlichen Wasserverbrauch bei einer beziehungsweise zwei Ernten im Jahr.

Die Ergebnisse zeigen einen Anstieg des Grünwassereinsatzes für die Produktion von Mais, Baumwolle, Soja und Weizen von 145 auf 263 km^3 pro Jahr im Zeitraum 1990 bis 2013. Dieser Anstieg ist zu einem großen Teil auf die Ausweitung der Anbaufläche für Soja zurückzuführen. Die Analyse von Managementszenarien zeigt, dass die Verbesserung des Nährstoffmanagements ein größeres Potenzial zur Verbesserung der Land- und Wasserproduktivität hat, als eine zusätzliche Bewässerung. Außerdem führt eine zusätzliche Bewässerung zu einer Verringerung der Wasserproduktivität trotz leichter Verbesserungen der Bodenproduktivität. Die Analyse von zweifacher Ernte pro Jahr in Soja- und Maisproduktionssystemen zeigt zwar eine höhere Wassernutzung, vermeidet aber die Ausdehnung der Anbauflächen und verbessert die Gesamtwasserproduktivität.

Diese Arbeit verbessert das Verständnis der aktuellen und zukünftigen Nutzung von Land- und Wasserressourcen, der Rolle der Intensivierung- und Expansionsprozesse, und der Wechselwirkungen zwischen Land und Wasser. Die Ergebnisse dieser Arbeit zeigen, dass die Ausweitung der Anbaugebiete in den letzten Jahrzehnten eine wichtige Triebkraft für die gesteigerte Verwendung von Grünwasser in Brasilien war, dass aber gleichzeitig verschiedene Intensivierungsprozesse zu einer produktiveren Nutzung von Wasser und Land geführt haben. Noch wichtiger ist, dass die Zunahme von zwei Ernten im Jahr eine Entkopplung zwischen der Bereitstellung von Wasser

und Land ermöglicht hat, was eine starke Zunahme der Wassernutzung ohne weitere Ausweitung der Anbauflächen ermöglicht.

PUBLICATIONS RELATED TO THIS DISSERTATION

JOURNAL ARTICLES

Flach, R., Skalský, R., Folberth, C., Balkovič, J., Jantke, K., Schneider, U.A., 2020. "Water productivity and footprint of major Brazilian rainfed crops – A spatially explicit analysis of crop management scenarios". *Agric. Water Manag.*, **233**, 105996. https://doi.org/10.1016/j.agwat.2019.105996

Flach, R., Fader, M., Folberth, C., Skalský, R., Jantke, K., 2020 *Environmental Research Commununications*. in press https://doi.org/10.1088/2515-7620/ab9d04

OPEN DATA

Flach, Rafaela. (2019). Water productivity and footprint of major Brazilian rainfed crops – a spatially-explicit analysis of crop management scenarios . Max Planck Society. https://dx.doi.org/10.17617/3.27

Flach, Rafaela. (2020). The effects of cropping intensity and cropland expansion of Brazilian soybean production on green water flows. Max Planck Society. https://dx.doi.org/10.17617/3.3x

CONTENTS

1 ON THE INTERACTION BETWEEN WATER AND LAND USE IN BRAZIL 1
1.1 Background 1
1.1.1 Agriculture at the center of global change 1
1.1.2 Modeling crop water requirements 4
1.1.3 Brazilian agriculture 5
1.2 Investigating water and land use in Brazilian rainfed agriculture 7
1.2.1 Research formulation 8
1.2.2 Building a modeling framework for Brazilian agriculture 8
1.3 Results and outlook 11
1.3.1 Summary of results 11
1.3.2 Conclusions 16
1.3.3 Outlook 18

BIBLIOGRAPHY 21

ARTICLES
2 WATER PRODUCTIVITY AND FOOTPRINT OF MAJOR BRAZILIAN RAINFED CROPS – A SPATIALLY EXPLICIT ANALYSIS OF CROP MANAGEMENT SCENARIOS 33
2.1 Introduction 35
2.2 Materials and methods 36
2.2.1 Study area and simulation units 36
2.2.2 General crop model characteristics 37
2.2.3 Simulation setup 37
2.2.4 Crop management scenarios 38
2.2.5 Water use and efficiency indicators 39
2.2.6 Data 40
2.3 Results 41
2.3.1 Yields and water productivity 41
2.3.2 Feasibility of supplemental irrigation 44
2.3.3 Water and land use under management scenarios 45
2.4 Discussion 47
2.5 Conclusions 48
3 THE EXPANSION AND INTENSIFICATION OF BRAZILIAN SOYBEAN PRODUCTION AND THEIR EFFECTS ON GREEN WATER FOOTPRINTS 53
3.1 Introduction 55
3.2 Methods 57
3.2.1 Data sources 57
3.2.2 Model setup 57
3.3 Results 59
3.3.1 Effects of expansion and intensification on soybean water footprints 59
3.3.2 Water use under single and double cropping systems 60
3.4 Discussion 63
3.4.1 Soybean production: larger water footprints, higher water productivity 63

3.4.2 Cropping frequency and improving agricultural water use assessments 63
3.4.3 Implications for green water use sustainability 64
3.5 Conclusions 65

APPENDICES

A APPENDIX TO CHAPTER 2 73
A.1 Extended methods 73
A.1.1 Simulation unit delimitation 73
A.1.2 Calculation of potential heat units 74
A.1.3 Selection of crop calendars and generation of new soil files 75
A.2 Model evaluation 76
A.3 Extended results 82
B APPENDIX TO CHAPTER 3 93
B.1 Background data 93
B.2 Extended methods 95
B.2.1 Model description 95
B.2.2 Data 96
B.2.3 Simulation units 96
B.2.4 Planting and harvesting dates 97
B.2.5 Potential heat units 99
B.2.6 General modelling framework 100
B.3 Detailed results 100
B.3.1 Sensitivity to cropping calendar scenarios 100
B.3.2 General model simulation results 103
B.3.3 Water footprints 105

LIST OF FIGURES

Figure 1.1 Harvested area and productivity changes in Brazilian agriculture between 1980 and 2018 6
Figure 1.2 Evolution of consumptive water use in Brazil 11
Figure 1.3 Scenarios and water productivities 12
Figure 1.4 Changes in production, harvested area, water use, and virtual water content 14
Figure 1.5 Annual evapotranspiration and water footprint for single and double-cropping 15
Figure 2.1 Geographical distribution of simulation units 37
Figure 2.2 Scenarios and water productivities 43
Figure 2.3 Irrigation potential and blue water stress 44
Figure 2.4 Evolution of consumptive water use 45
Figure 2.5 Scenarios of consumptive water use 46
Figure 3.1 Water footprint and virtual water content per year 59
Figure 3.2 Changes in production, harvested area, water use, and virtual water content 60
Figure 3.3 Virtual water content and annual crop evapotranspiration for single and double-cropping 61
Figure 3.4 Water footprints in single and double-cropping systems 62
Figure 3.5 Average monthly evapotranspiration for single and double cropping systems 62

LIST OF FIGURES IN APPENDIX

Figure A.1 Yields and water productivity for cotton 82
Figure A.2 Yields and water productivity for maize 83
Figure A.3 Yields and water productivity for maize second season 84
Figure A.4 Yields and water productivity for soybeans 85
Figure A.5 Yields and water productivity for wheat 86
Figure A.6 Blue/green water use ratio and yield increase for cotton, maize and maize second season 87
Figure A.7 Blue/green water use ratio and yield increase for soybeans and wheat 88
Figure A.8 Annual harvested area and consumptive water use for cotton 88
Figure A.9 Annual harvested area and consumptive water use for maize 89
Figure A.10 Annual harvested area and consumptive water use for soybeans 89
Figure A.11 Annual harvested area and consumptive water use for wheat 90

Figure B.1 Distribution of Brazilian regions and states 93
Figure B.2 Changes in soybean and maize production in Brazil 94
Figure B.3 Changes in maize production (main and second season) in Brazil 95
Figure B.4 Geographical distribution of double-cropping years 98
Figure B.5 Modeling framework flowchart 100
Figure B.6 Density distribution of GSET for all calendar options, for soybeans 101
Figure B.7 Density distribution of yields for all calendar options, for soybeans 101
Figure B.8 Density distribution of GSET and yields for all calendar options, for maize 102
Figure B.9 Density distribution of GSET for each evapotranspiration method, for all crops 102
Figure B.10 Geographical distribution of sensitivity to calendar and evapotranspiration methods 103
Figure B.11 Geographical distribution of average GSET for single and double cropping soybeans and maize 105
Figure B.12 Annual evapotranspiration for single and double-cropping 106
Figure B.13 Virtual water content for single and double-cropping 106
Figure B.14 Water use for single and double-cropping 107
Figure B.15 Ratio between GSET and total ET 107

LIST OF TABLES

Table 1.1 Data sources 10
Table 1.2 Potential water savings from yield gap closure 13
Table 2.1 Summary of scenarios 38
Table 2.2 Estimated yields and water productivity 42
Table 2.3 Growing season evapotranspiration for each crop 42
Table 2.4 Land and water savings 46
Table 3.1 Data sources 57

LIST OF TABLES IN APPENDIX

Table A.1 Classes of elevation, slope and soil texture used for delimitation of the homogeneous response units 74
Table A.2 General structure of the three model setups 76
Table A.3 Model setup for fertilization scenarios 76
Table A.4 Model setup for irrigation scenarios 76
Table A.5 Historical yields in Brazil for maize, soybeans, cotton and wheat 77
Table A.6 Average yields for every crop and scenario 78
Table A.7 Potential yields estimated in Mueller et al. (2012) 78
Table A.8 Consumptive water use and water productivity for every crop and scenario 79
Table A.9 Consumptive water use and water productivity values from Lathuillière (2011) 80
Table A.10 Values from Mekonnen and Hoekstra (2011) 80
Table A.11 Values estimated in Liu, Zehnder, and Yang (2009) 81

Table B.1 Harvested area per crop, for each Brazilian macro-region 94
Table B.2 Classes of elevation, slope and soil texture used for delimitation of the homogeneous response units 97
Table B.3 Average growing season evapotranspiration 104

1

ON THE INTERACTION BETWEEN WATER AND LAND USE IN BRAZIL

When most people think of water, their vision is limited to visible water,
such as a river system or a water supply scheme.
Water flowing through the root zone is thought of as soil,
water in the atmosphere as climate, and water quality as ecology.
Groundwater is seldom understood at all

— *Malin Falkenmark (Falkenmark, 1990)*

1.1 BACKGROUND

1.1.1 *Agriculture at the center of global change*

The sustainable management of the resources for sufficient production of food, feed, bioenergy and livestock will constitute one of the main global challenges to be faced in the coming decades. Meeting these growing demands for land-based products has required expansion and intensification of cropland, pastures and managed forests, as well as expansion of irrigated area (Ramankutty et al., 2018). Agriculture is at the center of four global future challenges: (i) to meet increasing demands for food, feed, biomass and bioenergy, (ii) to meet these demands while coping with scarcity of water and land resources, (iii) to mitigate its impacts on the biosphere through reduction of land use change and greenhouse gas emissions, and (iv) to adapt to global change.

One of the main ways agriculture and livestock imprint impacts on the biosphere is through conversion of natural habitat into cropland and grazing land. It is estimated that 80% of deforestation resulted from conversion to agriculture and grazing lands between 2000 and 2010, and Indonesia and Brazil only were responsible for over 50% of this tropical forest loss (Kissinger, Herold, and Sy, 2012). Both the agriculture-related land use change and the agricultural production itself are significant contributors of climate change, contributing to approximately 23% of total greenhouse gas emissions (IPCC, 2019). Land use change, in large part driven by agricultural expansion, is the source of the largest relative negative impact on biodiversity since 1970 (IPBES, 2019).

Agriculture and pastures already occupy around 40% of the land surface (Foley, 2005), and meeting future demands could lead to even greater increases in deforestation and biodiversity loss. Several thresholds of land occupation for cropland and pastures have been proposed in order to maintain acceptable biodiversity levels; Usubiaga-Liaño, Mace, and Ekins (2019) suggest that cropland and pastures should respectively be limited to 4.6 – 11.2% and 7.9 – 15.7% of global land area, much lower levels than the ones seen today, of approximately 15 and 25%.

The replacement of natural vegetation by cultivated and pasture lands also influences the local and global water cycle. When forests are replaced by crops, evapotranspiration normally decreases and consequently the local moisture recycling capacity is reduced; alternatively, irrigation tends to result in higher evapotranspiration and consequently reduction of surface flow (Gordon et al., 2005; Rost, Gerten, and Heyder, 2008). These changes can influence the local hydrological cycle and the regional climate, causing changes in precipitation in downwind or downstream regions (Keys and Wang-Erlandsson, 2018; Rockström et al., 2014).

Agriculture is also the biggest user of water as a resource (D'Odorico et al., 2018), as well as the main cause of disturbance to the terrestrial water cycle (Vörösmarty and Sahagian, 2000). Between 9 and 11% of evapotranspiration over land originates from cropland areas, of which around 86% - approximately $6.8x10^{12}$ m^3 per year - corresponds to green water (D'Odorico et al., 2019). Out of the total amount of blue (irrigation) water use in agriculture, around 50% originates from groundwater sources (D'Odorico et al., 2019).

__Green water__: the soil water held in the unsaturated zone, formed by precipitation and available to plants. __Blue water__: liquid water in rivers, lakes, wetlands and aquifers, which can be withdrawn for irrigation and other human uses As defined by Hoff et al. (2010).

The blue water used in agriculture comes from increasingly unsustainable sources, either from nonrenewable groundwater, or surface water withdrawals that compromise environmental flow requirements (Wada and Bierkens, 2014). Evidence shows that a large share of main watersheds globally have been overexploited (Falkenmark and Molden, 2008), and that human demand is close to reaching the limits for exploration of blue water sources worldwide (Gerten et al., 2013; Gleick and Palaniappan, 2010).

In this context, alternatives to sustainably increase the efficiency of agricultural production while halting expansion are vital to increase food production while greatly reducing the environmental impacts of agriculture (Foley et al., 2011). A rich literature has explored the global potential of intensification through different strategies, such as for example closing yield gaps (Davis et al., 2017a; Erb et al., 2016; Jägermeyr et al., 2015; Mueller et al., 2012; Rosa et al., 2018), increasing cropping frequency (Guilpart et al., 2017; Ray and Foley, 2013; Siebert and Döll, 2010; Wu et al., 2018) and shifting crops (Davis et al., 2017b).

The growing scarcity of blue water, however, is one of the main obstacles to intensification of existing cropland through the use of irrigation. Falkenmark and Rockstrom (2006) estimate that 3000 km^3 per year of blue water for agriculture would be necessary to alleviate hunger, while Davis et al. (2017a) estimate that, to close the crop yield gap globally, an additional 1315 km^3 per year of additional irrigation water would be necessary. Rosa et al. (2018), on the other side, estimate that in order to close the global yield gap while maintaining sustainable use of blue water resources, an increase of only 408 km^3 per year would be possible.

Other options for overcoming water constraints in food production include improving water productivity, expanding cropland into non-agricultural areas, and virtual water trade (Hoff et al., 2010). Global trade has been found to reduce the net water scarcity globally, as well as to promote water savings, as a result of trade between countries with different levels of water abundance and water productivity levels (Chapagain, Hoekstra, and Savenije, 2006; Fader et al., 2011; Konar et al., 2013).

Green water is currently the main water resource for agricultural production globally, and considering the great limitations of expansion of blue water use, green water is also considered a main unexplored resource for the future (Rockström et al., 2009). The two ways of expanding green water use is either by improving green water productivity - by increasing yields or implementing management options for reducing soil evaporation and harvesting rainwater - or expanding crop production into areas with availability of green water, appropriating water now consumed for plant growth in these systems (Falkenmark and Rockstrom, 2006; Rost et al., 2009).

Even though green water is responsible for most of the water resources used in agriculture globally, traditional water resources management has historically focused almost solely on blue water (Falkenmark and Rockström, 2010). The adoption and development of the blue and green water concepts has helped re-frame crop water management from the focus on irrigation infrastructure and surface water flows, to a more general way of looking at trade-offs between water and land use. On one side, increasing blue water consumption on current cropland through irrigation reduces blue water availability for other users and freshwater ecosystems downstream. On the other side, expanding agricultural land and thus increasing access to green water causes a loss of natural ecosystems. Overuse of blue water threatens the aquatic ecosystems that depend on them, while appropriation of green water threatens the terrestrial ecosystems that rely on green water for their biomass growth (Falkenmark and Rockstrom, 2006).

The sustainable limits to appropriation of green water are determined partly by local climate, but also the need to safeguard land for biodiversity (Schyns et al., 2019). The expansion of cropland in areas with high availability of green water is particularly problematic, as these are often also the areas with high rates of biodiversity, with water functioning in these landscapes to provide a numerous amount of ecosystem services. Nevertheless, a large share of the virtual water trade changes in the recent past have resulted from increased access to green water in countries with high rates of tropical deforestation, such as Brazil, Argentina and Indonesia (Carr et al., 2013). Beyond being the main resource for crop production and the main unexplored resource for the future, green water is also responsible for a large share of the changes in water use globally.

One of the aims of this doctoral thesis is to advance the understanding of land and water use interactions, by investigating rainfed agriculture with higher level of detail in Brazil. The chosen study area is nowadays one of the world's main virtual water exporters (Carr et al., 2013), and a region where the availability of green water and intensive agriculture is intimately related to expansion of agricultural land into important ecosystems.

The development of global and regional crop, water and dynamic vegetation models has promoted more accurate and spatially explicit estimations of water use in global agriculture, and evaluation of trade-offs between different management strategies. In Section 1.1.2 I discuss the importance and diversity of methods for modeling crop water requirements, and in Section 1.1.3 I describe in further detail the study area, and the current state of the Brazilian agricultural sector.

1.1.2 *Modeling crop water requirements*

Virtual water: amount of water 'embodied' in a product or service.

Water footprint: the total amount of water consumed to produce goods and services consumed by an individual or community (Hoekstra et al., 2011).

The concepts of *virtual water content* and *water footprint* were developed to improve the understanding of how much water is consumed to produce goods and services used by humankind, and how it moves across scales.

There is a diversity of methods and tools to estimate agricultural water use, and how water availability and stress influences agricultural production in different scales. The foundations of water balance models were developed already in the 60s and 70s, and initially focused on evaluating climatic constraints to agricultural development. Different methods for estimation of reference and actual evapotranspiration were developed after this, and in 1998 FAO published their Irrigation and drainage paper 56, providing guidelines and a standard for computing crop water requirements (Allen et al., 1998).

The CROPWAT tool, developed by FAO, was used in most of the early water footprint assessments, and also the recommended tool in the Global Footprint Manual (Chapagain and Hoekstra, 2003; Hoekstra et al., 2011). CROPWAT relies on the FAO Penman-Monteith evapotranspiration method described by Allen et al. (1998), a standardized table with crop parameters, the FAO's ClimWat database of climate data, and crop yields from the FAOSTAT database (Smith, 1992).

Later on, global water footprint assessments started to rely on a much more diversified range of global crop and water models. Some examples of these include H08 (Hanasaki et al., 2008), LPJmL (Bondeau et al., 2007), GEPIC (Liu et al., 2007), WaterGAP2 (Doell, Kaspar, and Lehner, 2003), GCWM (Siebert and Döll, 2008) and PCR-GLOBWB (Wada and Bierkens, 2014). The use of advanced global models enabled a more precise consideration of physical processes that influence agricultural water management, as well as to gain the ability to simulate a range of scenarios of climate change, agricultural management, irrigation application, among others.

Some of the models used for estimating global agricultural water footprints are classified as crop models (e.g. GEPIC and LPJmL), others as hydrological models (e.g. H08 and PCR-GLOBWB), or dynamic vegetation models (LPJmL) depending on the model's most important features (Wartenburger et al., 2018). Hydrological models routinely have a better representation of the influence of dams, reservoirs, underground water and river flow variability on the availability of water for irrigation. On the other side, crop models can better represent the effects of a range of agricultural management options on yields and water flows.

With the use of these models, global studies have been able to investigate the impacts on global water use by, for example, climate change (Fader et al., 2010), improvement of irrigation efficiency (Jägermeyr et al., 2015), population growth (Gerten et al., 2011), fertilizer and irrigation improvement (Liu and Yang, 2010), water harvesting (Hanasaki et al., 2010; Wisser et al., 2010), green water management strategies (Rost et al., 2009).

Unlike statistical, explanatory or empirical crop models, process-based (also known as mechanistic) crop models have the advantage to simulate diverse processes dynamically in response to external drivers, and thus compare effects of alternative decisions on trade-offs among those various responses (Jones et al., 2017; Siad et al., 2019).

In this PhD thesis, the dynamic process-based EPIC model was chosen to simulate the effects of different crop and water management options on agriculture in Brazil. The EPIC model was developed initially to simulate soil erosion processes, and has been expanded to represent processes related to weather, crop water use, soil temperature, erosion-sedimentation, nutrient cycling, tillage, crop management and biomass growth (J. R. Williams et al., 1989; Philip W. Gassman et al., 2004). EPIC has no spatial component, and therefore cannot represent hydrological processes on a watershed level. The APEX model was developed based on the EPIC model, and includes livestock and hydrological processes on a watershed level (Gassman and Williams, 2009).

Due to the aforementioned lack of a spatial component, however, EPIC is a very versatile model that can be adapted for application in any scale, from the farm to the global level. The GIS version of EPIC, named GEPIC, has been extensively applied to estimate crop water relations globally (Liu, Zehnder, and Yang, 2008; Liu, 2009; Liu et al., 2007; Liu and Yang, 2010). EPIC has also has been calibrated and validated on the national and regional scales to simulate crops, for example, in Europe (Balkovič et al., 2018, 2013), United States (Niu et al., 2009), and Sub-Saharan Africa (Folberth et al., 2012). The model has been used as a tool to simulate a wide range of agricultural and environmental-related processes, from the effect of tillage and crop rotation, to climate change (Philip W. Gassman et al., 2004).

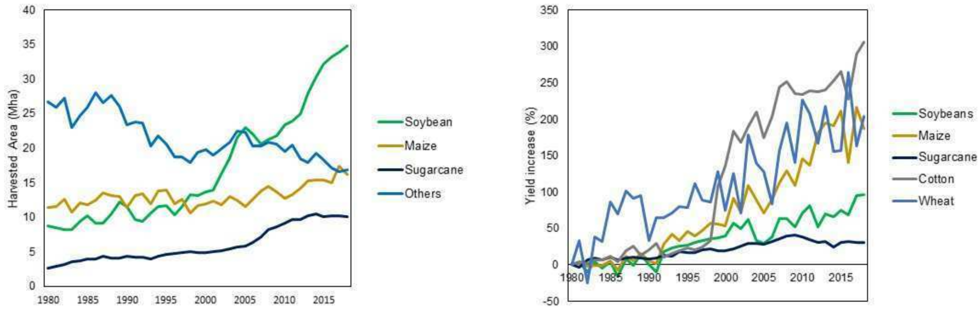
The implementation, calibration and validation of the EPIC model is riddled with challenges, in large part due to the great number of model parameters and input data (Wang et al., 2012). The approach I developed to apply the EPIC model to simulate crop water relations in Brazil and answer the research questions that drive this thesis is explained in higher detail in Section 1.2.2.

1.1.3 *Brazilian agriculture*

Brazilian agriculture is central to the water-land-food nexus described in Section 1.1.1, and is the focus of this research work. Brazil is a country with abundant water and land resources, which has become one of the most important producers and exporters of agricultural commodities globally. The pronounced changes the Brazilian agricultural sector has undergone in the recent decades include steep increases in productivity, a rampant expansion of cropland and pasture areas into vulnerable ecosystems, as well as its establishment as a main producer in the global bioeconomy.

The accumulated harvested area of the country's nine main crops – soybeans, maize, sugarcane, beans, wheat, coffee, rice, cassava and cotton – amounts to around 92% of the total harvested area, of which soybeans, maize and sugarcane are responsible for 78% (IBGE (Brazilian Institute of Geography and Statistics), 2018). Between 2000 and 2014, the total cropland area roughly doubled, growing from 26 to 46.1 10^6 hectares, and 20% of this expansion came from conversion of natural vegetation (Zalles et al., 2019). Figure 1.1a shows the increase in harvested area for the country's main crops between 1980 and 2018, with a marked growth in harvested area for soybeans and sugarcane.

Dias et al. (2016) and Rudorff et al. (2010) found that the expansion of sugarcane happened mainly over pastures and summer crop areas. The expansion of soybeans, on the other side, is one of the drivers of conversion of natural habitat in agricultural frontiers – the expansion of soybean harvested area has been in part possible through conversion of pastureland, and in part by cropland expansion into sensitive ecosystems, namely in the Amazon and Cerrado biomes (Gibbs et al., 2010).



(a) Harvested area per year (10^6 hectares) (b) Yield increase relative to 1980 (%)

Figure 1.1: Harvested area and productivity changes in Brazilian agriculture between 1980 and 2018. Source: (IBGE (Brazilian Institute of Geography and Statistics), 2018)

Even though the harvested area of maize has remained relatively steady (Figure 1.1a), the cropland area dedicated exclusively to production of maize has decreased as a result of the growth of maize production as a second crop, mostly in soybean-maize double-cropping systems. While in 2003 around 25% of the harvested area of maize in the country corresponded to *safrinha* maize, in 2018 this share grew to 70%, and thus most of the country's maize production is of *safrinha*[1] maize. Only in the Brazilian state of Mato Grosso, the double-cropped area increased from approximately 0.5 to 2.9 million ha between 2001 and 2011 (Spera et al., 2014).

Double cropping is here defined as the planting of two crops sequentially in the same crop year.

Alongside this cropland expansion, the intensification of Brazilian agriculture led to marked increases in land productivity: between 1990 and 2001, yields grew from 1.7 to 2.9 and 1.8 to 4.3 tons per hectare for soybeans and maize, respectively (Dias et al., 2016). Figure 1.1b presents the percentage of yield increase of Brazilian main crops relative to 1980, demonstrating the changes in land productivity in the recent decades. These intensification patterns were observed both in frontier and established agricultural areas, and were driven in large part by technological improvements such as liming, fertilization, adoption of no tillage systems, cultivation of cover crops, double-cropping and genetically modified crops (Barretto et al., 2013).

The Brazilian Water Agency (ANA, in Brazilian Portuguese) estimates that the agricultural sector is responsible for 67.1% of total blue water use. The irrigated area has increased from 1.5 to 6.9 10^6 hectares between 1980 and 2015, and the main irrigated crops are sugarcane and rice, responsible respectively for 22 and 29% of the total irrigated area in 2015, followed by other crops irrigated in central pivot systems (20%) (ANA, 2017). The central pivot type of irrigation is usually applied for the production of grains, among them cotton, beans, maize and soybeans. The Brazilian Water Agency estimates that irrigation could reach 10.09 million hectares in 2030, with the growth happening mostly in central pivot systems (ANA, 2017).

Agriculture is both a user of water resources and a driver of changes in the water cycle. One of the main concerns related to the cropland and pasture

1 The second season crops planted in double-cropping systems are called *safrinha* crops in Brazil.

expansion into previously forested areas in Brazil is the reduction of overall evapotranspiration from land. The biomes with highest rates of deforestation currently – the Amazon and the Cerrado – have been identified as important sources of moisture recycling throughout the continent. The replacement of natural vegetation by pastures and cropland in the Amazon forest area has been pointed out as a source of changes in the local evapotranspiration cycle that could lead to the increase of drought conditions in this biome (Nobre, 2014). Keys, Wang-Erlandsson, and Gordon (2016) found that land use change in Mato Grosso - a state in the Amazonian frontier with the highest rates of soybean production - could affect a diffuse region downwind, including the cities of São Paulo and Rio de Janeiro.

Even though the local availability of water is highly heterogeneous, Brazil is overall abundant in both blue and green water resources (ANA, 2013; Flach et al., 2016). As a result of the combination between high water resource availability and agricultural export output, Brazil was identified as the world's top net exporter of virtual water in 2010 (Carr et al., 2013). Brazil exports around 54.8 billion m^3 of virtual water per year, mainly to Europe and China (Silva et al., 2016b).

Studies that estimate water footprints in Brazilian agriculture are mainly focused on a local or regional scale (Albuquerque, 2013; Bleninger and Kotsuka, 2015; Carvalho and Menezes, 2014; Lathuillière, Bulle, and Johnson, 2018; Lathuillière, Coe, and Johnson, 2016; Lathuillière et al., 2018a; Lathuillière, Johnson, and Donner, 2012; Lathuillière et al., 2014). Flach et al. (2016) analyzed water footprints and virtual water trade from Brazilian commodities on a national scale by using the results from previous global water footprint studies (Mekonnen and Hoekstra, 2011), while Silva et al. (2016b) used results from FAO's CropWat model. The GLOBIOM-Brazil project, one of the main efforts to model land use change processes in Brazil at a national scale, is based on a global EPIC model with a spatial-explicitness of 121 thousand simulation units across the globe, with the base data in a 5 degree resolution.

1.2 INVESTIGATING WATER AND LAND USE IN BRAZILIAN RAINFED AGRICULTURE

One of the challenges in modeling water use in agriculture is to reconcile different scales of analysis and levels of complexity. A great deal of effort has been devoted in previous literature on one side to model agricultural water use globally, and on the other side to measure water use in Brazil locally. Nevertheless, a deeper understanding of the changes in water and land use within the country's boundaries is called for, due to the dominance of Brazilian agricultural production in the global virtual water trade, and the observed environmental impacts of water and land use.

This PhD thesis aims to fill this gap by analyzing Brazilian agricultural water use on a national scale. With further consideration of the relative importance of green water as a main resource for agriculture presently and in the future, this research work focuses on modeling water use in rainfed systems. Therefore, I focused here on the country's four main rainfed export crops: soybeans, maize, cotton and wheat. In the second part of this research work, I give further attention to soybeans and maize, the two crops with the highest share of harvested area, and which have undergone pronounced changes in the recent decades.

The main general objectives addressed throughout this thesis are to understand how water and land use have evolved in the last decades in Brazil, and to investigate how water and land use could change under different scenarios of management and irrigation. For this, I developed of a modeling infrastructure for analyzing scenarios of water and land in Brazilian agriculture on a national scale, with high spatial-explicitness.

In this section I first describe in detail the research questions that were addressed in this thesis (Section 1.2.1), and then describe the modeling approach developed to answer these questions (Section 1.2.2).

1.2.1 *Research formulation*

The four research questions I describe here are meant to address the aforementioned objectives of this PhD thesis. The first two questions are addressed in detail in Chapter 2 and the second two questions in Chapter 3.

First research question

How has green water use for Brazilian main rainfed crops changed in the recent decades?

This thesis comprises one of the first studies to model agricultural water footprints for Brazilian agriculture at a national scale, with high spatial-explicitness and updated input data. Assuming rainfed conditions, I estimated the water use in the period 1990-2013 for soybeans, maize, cotton and wheat.

Second research question

What is the potential for improvement of land and green water productivity for Brazilian rainfed crops, with and without irrigation?

Besides analyzing land and water interactions for agricultural production for the recent past, I also investigated scenarios of agricultural management and irrigation, with the aim to understand not only the recent changes, but also possibilities for the future. Six scenarios of agricultural management were simulated, of which two included the implementation of supplemental irrigation.

Third research question

How have intensification and expansion of soybean production in Brazil influenced green water use?

Both the expansion and intensification of production of soybeans and maize has had significant impacts on land and water use. I investigate the changes in water and land use in the recent past, analyzing in greater detail the role of agricultural management and cropland expansion. Intensification is taken into consideration with two different approaches, first by accounting only temporal changes in yields, and then considering also changes in cropping intensity through the growth of double-cropping.

Fourth research question

What is the influence of double-cropping on the land and water footprints of soybeans and maize?

Multiple cropping is commonly not taken into account in agricultural water use assessments. Neglecting the effects of cropping frequency in the estimation of green water use could have implications also on the sustainability of green water use. I therefore estimated the influence of double-cropping as a type of intensification in water and land use, and estimated the biases between the estimation of water use with and without consideration of double-cropping.

1.2.2 *Building a modeling framework for Brazilian agriculture*

To answer the research questions described above, the biophysical crop model EPIC was employed to simulate crop water processes. Initially developed to simulate soil erosion and soil productivity processes, the EPIC model was expanded to become a robust tool to address the major environmental processes related to crop growth. The current version of the EPIC model is documented by Williams, Izaurralde, and Steglich (2008), and its application documented by Williams et al. (2015). The model comprises ten different components, which simulate weather, hydrology, erosion-sedimentation, nutrient, pesticide fate, plant growth, soil temperature, tillage, economics, and plant environment control.

The EPIC model contains a large number of crop and model parameters, as well as of input data. The calibration and validation of the model over a large amount of areas is a challenge, since (i) there are usually no comprehensive experimental or independent data available that allow testing of the entire set of variables represented in the model, and (ii) aggregated data from regional statistics are usually insufficient as they do not represent field-scale conditions for which the models have been originally developed (Balkovič et al., 2013). Another challenge of implementing the model on a larger scale is that integrating data in different scales can lead to aggregation errors, which can influence the temporal and special accuracy of model predictions (Hansen and Jones, 2000).

One issue commonly found when calibrating models on large-scale simulations is that, by adjusting model parameters to "statistically fit" experimental data has the potential to reduce the model's mechanistic structure to an empirical exercise, and hinder its ability to perform beyond the range of data used for the calibration (Niu et al., 2009). Here I used an approach inspired by the methodology used in Balkovič et al. (2013), in which (i) the default biophysical process parameter values in EPIC were accepted (with only minor adjustments), (ii) reviewed crop parameters based on average cultivar characteristics for the selected crops were used for the entire study area, (iii) sensitivity analysis and adjustment for main management parameters, namely sowing dates, length of growing season, and potential heat units, were performed.

In order to cope with the issue of aggregation errors, I adopted a methodology of delimitation of homogeneous response units (HRUs), inspired by the approach developed for the GEOBENE global database for bio-physical modeling (Skalský et al., 2008). With the use of soil and elevation maps with a resolution of 1 km, I classified the Brazilian territory in classes of altitude, slope and soil texture. Every unique combination of these classes was considered a distinct HRU. These units were further divided, according to land use and political boundaries (more specific descriptions of this methodology can be found in Appendix A and Appendix B). In the end of the delimitation process, a number of simulation units in the order of magnitude of 10^4 was obtained. The number of simulation units varies for each crop and simulation, depending on the extent of the area where each crop is produced, and the land cover product used for the delimitation of the simulation units.

In Chapter 3, I used the product developed by Dias et al. (2016), with the extent of harvested area for soybeans and maize in Brazil through time. Since this database is only available for soybeans and maize, Chapter 2 required a different approach in which a combination of the ESA Land Cover product (ESA, 2017), and the database of harvested area per municipality from IBGE (Brazilian Institute of Geography and Statistics) (2018) were used.

The high spatial-explicitness of the simulations of the research work presented in this PhD thesis contributed to reduce the aggregation errors in the model simulations, however increased significantly the processing time necessary. The

0810 version of the model source code in FORTRAN was compiled and modified for parallel processing in a Linux environment, to make it capable of parallel simulations over a large number of simulation units and scenarios.

While developing the modeling general framework, the selection of updated high-resolution data for soil, weather, elevation, land use and management was one of the most important steps for improving the model accuracy and representing the physical diversity of the Brazilian territory. Table 1.1 summarizes the data sources of physical characteristics used as input to the model.

Table 1.1: Summary of data sources.

Type	Source	Resolution
Weather	Daily gridded meteorological variables in Brazil (1980–2013) (Xavier, King, and Scanlon, 2016).	0.25°
Soil	SoilGrids250: Global gridded soil information based on machine learning (Hengl et al., 2014).	1 km
Terrain	SRTM 90m Digital Elevation Database v4.1 (Jarvis et al., 2008).	90 m
Land Use	Patterns of land use, extensification, and intensification of Brazilian agriculture (Dias et al., 2016).	1 km
Land Cover	ESA: Land Cover CCI Product (ESA, 2017).	300 m

The sensitivity analyses performed reaffirmed that the model is particularly sensitive to the sowing dates and length of the season. The crop calendars used in Chapter 2 were obtained from the global database developed by Sacks et al. (2010), and present different sowing and harvesting date ranges for different zones within the Brazilian territory. In Chapter 3, the database of planting windows for single and double-cropping soybeans was obtained from Abrahão and Costa (2018), which provides yearly planting windows with a resolution of 1 degree. There are a variety of available datasets for global planting and harvesting dates (e.g. MIRCA2000 (Portmann, Siebert, and Döll, 2010) and SAGE (Sacks et al., 2010)), as well as methods to determine optimal planting and harvesting dates (e.g. Waha et al. (2012) and Balkovič et al. (2013)). While the calendar databases can be unrealistic due to not considering interannual climate variability, the methods that estimate optimal planting dates assume that farmers make "perfect decisions" regarding planting and harvesting periods. My approach constituted a hybrid between these two approaches: based on the planting windows available in the crop calendar datasets, a variety of crop calendar options was simulated, and the options with higher overall yields were selected.

I found that the final model results represented reasonably the response of crops to changes in fertilization and weather variables, for most crops. The results did not adequately represent low yields, in part because the model does not simulate processes that generally induce crop failures such as pests, land abandonment and economic changes. I also found that maize yields were slightly overestimated, which has been found previously in EPIC modeling studies (Balkovič et al., 2013).

The main limitation and challenge in modeling Brazilian agriculture is to be able to represent both its temporal and geographical complexities. The access to fertilizers has increased significantly in the recent decades, leading to changes in the distribution and scale of nutrient application rates. Furthermore, a large range of new seed varieties has been developed, which are suited for different areas of the country. Despite not capturing some of these intricacies, our modeling approach contains a much higher level of detail when compared to other large-scale crop modeling studies that include Brazil as one of their geographical units, and is one of the first steps towards a better understanding and modeling of Brazilian agriculture.

1.3 RESULTS AND OUTLOOK

This doctoral thesis makes a step forward in the analysis of changes in green water use in Brazil, and in the relationship between land and water use change in this setting. In the following section I will summarize its main results, discuss their limitations and implications, outline innovative aspects related to the work presented here, and give recommendations for future work.

1.3.1 *Summary of results*

Here I summarize and discuss the most important results presented in Chapter 2 and Chapter 3. Having in mind the model and data uncertainties discussed in Section 1.2.2, the following general conclusions can be drawn:

• *During the period between 1990 and 2013, green water used for the production of maize, cotton, soybeans and wheat increased from 145 km^3 to 263 km^3 per year.* *First research question*

In the same period, the harvested area grew from 26 to 46 million hectares, and the production from 46 thousand to 171 thousand tons per year (IBGE (Brazilian Institute of Geography and Statistics), 2018).

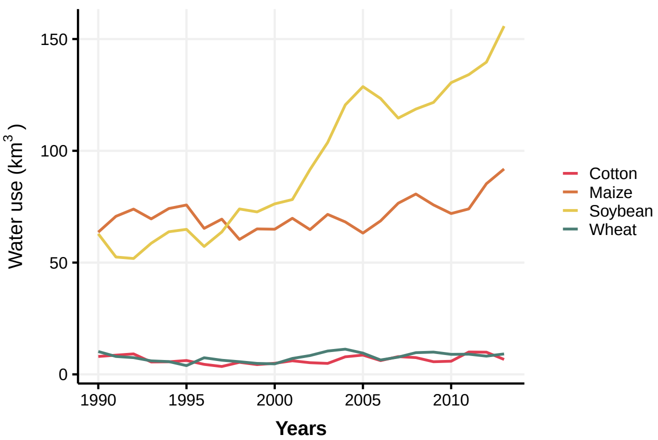


Figure 1.2: Total consumptive water use per crop in the period 1990-2013 (km^3), considering historical harvested area per municipality and estimated green water use.

As seen in Figure 1.2, these changes are in large part related to growth of soybean production and harvested area. The water use for maize shown here was estimated assuming that all maize was planted as a single crop. According to Table 2.3, those values would be lower if considering a part of the maize production as a second crop, i.e. in a double-cropping system.

To put these numbers into perspective, the Brazilian Water Agency estimates that the current amount of irrigation water used in the entire agricultural sector corresponded to 23.5 km^3 (745 10^3 l/s) in 2017, with a projection to increase to 33.4 km^3 (1,055 10^3 l/s) in 2050.

Second research question

- *Supplemental irrigation for main rainfed crops (soybeans, maize, cotton and wheat) would lead to increases in land productivity, albeit with decreases in water productivity.*

Chapter 2 presents results of water productivities and yields for historical data, and for six scenarios of agricultural management. The subsistence scenario refers to a model setup with no fertilizer application, while the high-input scenario refers to a model setup where nutrient stress is minimized by automatic nutrient application. The mid-input scenario, on the other side, refers to levels of nutrient application coherent with moderately intensive agriculture (further detail on scenarios, see Appendix A). The irrigated scenarios assume that water stress levels above 20% are counteracted by automatic irrigation, and the rainfed scenarios assume no irrigation application. Here, supplemental irrigation refers to the automatic irrigation aimed to reduce water stress levels.

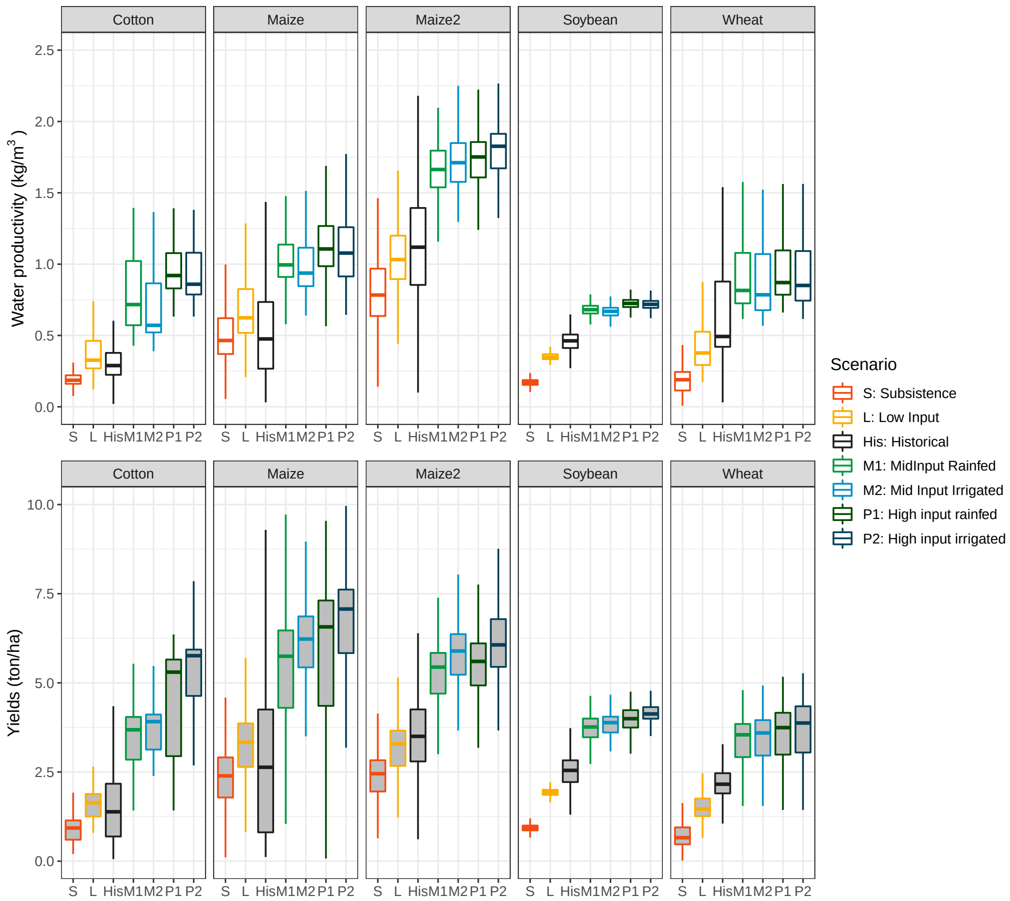


Figure 1.3: Water productivity (above, kg/m^3) and yields (below, ton/ha) statistics per municipality, related to historical data and management scenarios, for all crops.

I define here the yields in the high-input irrigated and the high-input irrigated scenarios as the 'yield potential' and 'water-limited yield potential'. Therefore, 'closing the yield gap' is defined as the transition from the 'historical' to the 'high-input' scenarios, with implementation of supplemental irrigation (in the case of 'historical' to 'high-input irrigated') and without (in the case of 'historical' to 'high-input rainfed').

Figure 1.3 shows that closing the yield gap with and without irrigation would lead to increases in water productivity in the order of 0.5-1.5 incremental kilos of product per cubic meter of water use. It is evident for all crops, however, that the increases in yield caused by irrigation are not as striking as the ones related to increase of nutrient input. The opposite is the case for water productivity, as the scenarios with supplemental irrigation show lower levels of water productivity for all crops.

The crops with more pronounced response to supplemental irrigation are cotton and second season maize. The planting of second season maize is usually done after harvesting of soybeans, and is mainly limited by the length of the rainy season. The productivity and feasibility of this crop would therefore benefit greatly from supplemental irrigation. In the case of cotton, a large share of cotton production happens in the northeast area of Brazil, which is also one of the driest and water scarce areas of the country (as seen in Figure 2.3c), and this region is where most of the benefits from supplemental irrigation of cotton are seen (regionally detailed results in Appendix A).

The results from the scenarios shows both the potential of agricultural intensification to make better use of already available green water. In the case of the crops analyzed, the results also show that supplemental irrigation plays a much less pronounced role in intensification of agricultural production. One limitation of these results is that the crop calendars are static across the different scenarios, and in the case of some of these crops, supplemental irrigation could enable shifting or extending the cropping season.

- *Closing yield gaps could lead to green water savings in the order of 20-50%.* *Second research question*

In Chapter 2, I calculated the amount of water that would be necessary to produce the same amount of crop output, considering the increases of water productivity related to closing yield gaps (Figure 1.3, Table 1.2). Here, water saving is defined as the difference between the amount of water necessary to produce under current conditions and under yield gap closure in rainfed conditions, divided by the amount of water necessary to produce under current yields. The results are averaged across the territory, and across the 24 years between 1990 and 2013.

Table 1.2: Potential water savings from yield gap closure (%).

	Cotton	Maize	Soybean	Wheat
Water savings (%)	52	29	37	46

The results shown in Table 1.2 assume closing yield gaps without the implementation of irrigation. The amount of water savings in this case would be tightly connected to the reduction of land requirements driven by higher productivity. Along with less area, less green water appropriation would be necessary for production of these crops. Cotton is the crop which shows the biggest improvements, followed by wheat. The biggest gaps are observed in the period between 1990 and 2000, after which the production of wheat and cotton became more productive (Figure A.5 and Figure A.5).

Third research question

• *Increase in harvested area has been a major driving force in the increase of green water appropriation in Brazil in the last decades, particularly for production of soybeans. Improvements in productivity had a less pronounced role, however have led to an increase in the amount of crop obtained per drop of water used throughout the country.*

In the first part of Chapter 3, I analyzed in further detail the changes in water use for production of soybeans in Brazil between 1990 and 2013, and analyzed the different role of expansion and intensification in water use. Figure 1.4 shows the normalized relative change in production, harvested area, water use and virtual water content, using 1990 as baseline. In these results, I assume that soybean production is grown only in single-cropping conditions.

As seen in Figure 1.4, the increase in green water footprints for soybean production and the increase of harvested area happened mostly as a consequence of cropland expansion, accompanied with a steady increase in water productivity. The virtual water content of soybeans in 2013 reached an average of around 2000 m^3/ton, a value similar to the ones found in highly productive areas of soybean production globally (Tuninetti et al., 2015).

It is also possible to note a de-coupling between the increases in harvested area and water use, and the increase in production. While the output of soybeans grew 308% during this period, the harvested area and water use increased 143 and 156%, respectively. The virtual water content was reduced by 37%.

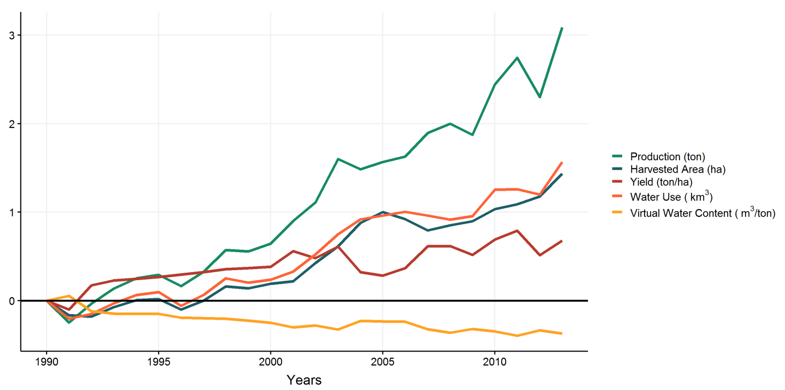


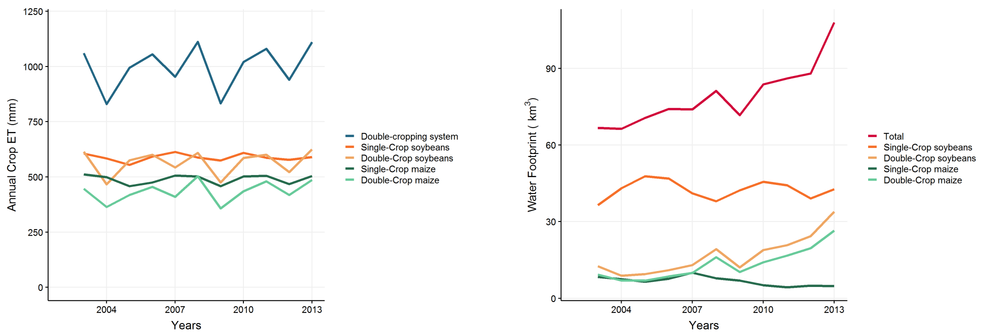
Figure 1.4: Rate of change for production, harvested area, water use and virtual water content for soybean production between 1990 and 2013.

The increase in water footprints from 61 to 156 km^3 during this period is largely related to the expansion of soybean harvested area. Most of the additional 95 km^3 of appropriated green water resource became available to the international market as virtual water, as a large share of Brazilian soybean production is intended for the external markets in the European Union and China (Godar et al., 2015).

Fourth research question

• *Double-cropping has played a major role in increasing water appropriation while avoiding cropland expansion, improving overall water productivity.*

In the second part of Chapter 3, I analyzed the effect of double-cropping practices on green water use for soybean and maize production in two Brazilian states, the states of Paraná and Mato Grosso. The soybean-maize double-cropping system is the main form of multi-cropping practice in Brazil, and has spread considerably across the country in the last decades (see Section B.1). The chosen states are not only solely responsible for about 50% of the country's production of soybean and maize, they are also the areas where double-cropping soybean-maize systems are widespread. Adding a second crop after the harvest of soybeans is possible due to the development of cultivars with shorter cropping lengths, but it also depends on the yearly length of the rainy season. For these reasons, the feasibility of double-cropping has been spreading across the country, but still not all years are considered feasible for implementation of this practice. Mato Grosso and Paraná are also the areas where double-cropping has been adopted more consistently over time in the period between 2003 and 2013 (Figure B.4).



(a) Annual evapotranspiration (mm) for single and double-cropping

(b) Water footprint (km^3) for single and double-cropping

Figure 1.5: Comparison of annual evapotranspiration (mm, top) and water footprint (km^3) for crops grown under single-cropping and double-cropping conditions.

I found that the growing season evapotranspiration for double-cropping crops is in general lower due to a shorter cropping season, and presents higher interannual variability, as shown in Figure 1.5a. In the double-cropping system, the yearly crop evapotranspiration in a given area is the sum of the growing season evapotranspiration for the two crops. As a result, the water use per unit of area is significantly higher than any of the other single crops on their own. I estimated that the average annual evapotranspiration of soybeans and maize production across the territory of the two states would equal to about 560 mm/year, if considering that the two crops were planted independently as single crops. However, by considering the mixture between single-cropping systems, and cropland area different than the total harvested area, the average evapotranspiration would correspond to 685 mm/year.

The increase of water footprints per area (i.e. average annual evapotranspiration) related to double-cropping systems is a sign of a greater appropriation of green water available across the annual precipitation cycle, as shown also in Figure 3.5. The nearly linear relationship between expansion of harvested area and water use observed in the previous results remains, but there is de-coupling between the increase of actual cropland area and water use. In the same way that double-cropping causes a gap between harvested area and actual cropland area, it also changes the relationship between cropland area and green water use.

Taking double-cropping also influences total water footprint estimations, as seen in Figure 1.5b. The total water footprint of soybeans and maize increased by 40 km^3 between 2003 and 2013 in the selected states. Out of this increase in water footprints, 13 km^3 (32%) happened in double-cropping systems. In 2013, 26 km^3 (24% of the total footprint for that year) was dedicated to second season maize. This means that around a quarter of the additional green water resources appropriated in this period in the two states required no expansion in cropland area.

1.3.2 *Conclusions*

In the following I will present the main conclusions of this doctoral thesis, discuss on the relevance and limitations of the presented results, and after that, offer an overview of the innovative aspects included in this work.

Main conclusions

This thesis makes a step forward in the analysis of current and future use of land and water, the role of intensification and expansion processes, and interactions between land and water use. It comes to the main conclusion that harvested area expansion has been a major driving force in the increase of green water appropriation in Brazil in the last decades, but that different intensification processes have led to a more productive use of water and land over time. More importantly, that the growth of double-cropping has allowed the decoupling between the appropriation of water and land, allowing a great increase of water use without further expansion of cropland.

Relevance and limitations

Although the aforementioned conclusions might be unsurprising in qualitative terms, the scale of the changes observed and projected in the results is key to their relevance. That is particularly the case for two main results, which I will discuss here.

First, the growth in estimated green water use from 145 to 263 km^3 per year for the four selected crops from 1990 to 2013 demonstrates the importance of the changes in land use in rainfed crops not only for availability of water for agriculture in Brazilian agriculture, but also for the transport of virtual water resources for the international market. On one side, the total amount of blue water used in Brazilian agriculture in 2017 estimated by the Brazilian Water Agency equals to less than 9% of the total amount of green water used by only the four main rainfed crops in 2013. This shows the greater relative importance of green water resources, especially the ones appropriated by these four main crops, when compared to blue water use in irrigated agriculture. On the other side, Carr et al. (2013) identified that, in 2010, Brazil became the world's main virtual water exporter, with about 187 km^3 exported in 2010. This scale of resource re-allocation is only possible with the changes in green water use described in this thesis. Therefore, the results presented in this thesis demonstrate how the increased virtual water exports were made possible, and where and how this increase in resource appropriation happened.

Second, the analysis of water use in double-cropping systems shows how changes in cropping frequency can change the relationship between green water and land use. One of the ways cropping frequency is defined is as the relationship between harvested area and cropland area (Ray and Foley, 2013). As green water use is a function of the harvested area, an increase in cropping frequency through multi-cropping practices leads also to a different relationship between green water use and cropland area. The results from this thesis show that, in the case of soy and maize production in two Brazilian states, around 24% of water use in 2013 happened without expansion of cropland, i.e. in the production of a second crop. Furthermore, out of the increase in water use between 2003 and 2013, 32% corresponded to increase in water use for production of second season maize. Therefore, almost a third of the increase in green water use for soybeans and maize in those two states was not a result of a corresponding increase in cropland area. This has implications for how we understand the limits to the availability of green water locally and globally.

The implications of the study results are diverse, but certainly dependent on a number of factors. Water footprint assessments in their most strict form are designed to estimate volumetric use of water in production of goods, but they don't necessarily elaborate on the environmental impacts or sustainability of this water use (Lathuillière et al., 2018b; Quinteiro et al., 2015; Ridoutt and Pfister, 2010). The scope of the research presented in this thesis is limited to the estimation of volumetric estimates of water use, and does not attempt to analyze also impacts and sustainability of resource use, or how the resource use is transferred across scales through trade.

Another limitation of the research presented here is the fact that the processes of agricultural intensification and expansion are seen only through the lenses of their influence on water use. Therefore, in this thesis I do not take into consideration the potential environmental impacts that are normally connected to increased use of fertilizers, development of cultivars, deforestation and other processes related to intensification and expansion of agriculture. The same can be said regarding related economic and social aspects.

Due to the aforementioned limitations, the results of this thesis can only be policy informative if they are considered not on their own, but rather as part of a broader context. Aspects that should be taken into account in conjunction with the presented results include careful consideration of related social and environmental impacts, as well as trade-offs across different scales.

Innovative aspects

I would like to highlight two main innovative aspects within this work: (i) the development of a modeling infrastructure to simulate water use Brazilian rainfed agriculture on a national scale, with a high level of spatial-explicitness and up to date input data, (ii) the analysis of the effect of double-cropping practices on green water use.

Regarding the second aspect, one of the reasons why there are few previous studies analyzing the effect of cropping frequency on water use is in large part due to a general lack of data on multi-cropping practices globally. Recent studies have used satellite data to map and estimate cropping frequency across different areas (Biradar and Xiao, 2011; Siebert and Döll, 2010; Yan et al., 2014; Zhao et al., 2016). However, sub-national statistics on production and harvested area dedicated to multiple cropping is more rare. In the case of Brazil, the data on second season maize production is only available after 2003, and is not consistently available across the country. The analysis of double-cropping practices in this thesis focuses in the states of Parana and Mato Grosso, as these are the areas where the most reliable data is found. Furthermore, there is a great diversity of crop combinations that make up different types of rainfed and irrigated multi-cropping practices around the world (Guilpart et al., 2017). This diversity makes the consideration of multi-cropping practices a challenge in larger-scale water footprint assessments.

1.3.3 *Outlook*

The research presented in this thesis sheds light upon the interactions between water and land use in agriculture, how these have changed in the recent past, and potential future changes. The results and methodological approach presented here could be a relevant starting point to answer other important research questions. Analyzing the economic mechanisms driving these changes in resource use, and the impacts of the use of these resources, are some of a number of opportunities for a potential continuation of this research work.

By coupling the results of this study with trade data, it would be possible to investigate how much of the observed changes are linked to domestic and foreign consumption, and which global consumers are connected to them. The modeling structure developed here could also provide useful input for economic models that analyze land use and the agricultural sector, such as GLOBIOM-Brazil.

Another very interesting avenue of investigation following the one described in this thesis would be to analyze not only how water and land resources are appropriated, but also connect that to the impact of the use of these resources. For this, it would be required to take into consideration detailed information on the types of land use transitions that have happened in this period, and estimation of the water fluxes in the different natural and human-mediated states.

There are, certainly, many opportunities to build up on the research work presented here by expanding its scope. This research was dedicated to investigating green water and land use change processes in Brazil, and therefore focused on the country's main rainfed crops. Changes in the scope would naturally fit different storylines, for example (i) including modeling of sugarcane and rice would enable analyzing the country's main water users of both blue and green water, (ii) analyzing also the expansion of extensive and intensive pastures would allow an analysis of the country's main drivers of land use change, and (iii) including all crops, livestock and forestry would enable modeling the entire country's agricultural sector.

Another natural step for continuation of this research work would be to attempt at reducing the uncertainties in the modeling framework presented. One of the observations from the simulations performed is that the values of consumptive water use of crops are very sensitive to the sowing dates and the length of the growing season, as has been observed before in the literature (Tuninetti et al., 2015). The studies presented in Chapter 2 and Chapter 3 applied different datasets for planting and harvesting dates. These datasets were developed with different methodologies, and present different levels of spatial-explicitness. Future research could elucidate the differences in estimated yield and water use between different datasets such as MIRCA2000 (Portmann, Siebert, and Döll, 2010) and SAGE (Sacks et al., 2010), and different methods that estimate yearly optimal planting and harvesting ranges. The Brazilian Ministry of Agriculture currently provides annually the Agricultural Climate Risk Zoning

System (ZARC, in Portuguese), which identifies optimal planting and harvesting dates across the country for different soil and elevation classes, and recommends optimal cultivars. Even though this will constitute an invaluable dataset for future modeling efforts, the data is only available after 2016.

The diversity of crop cultivars is another source of bias that can be addressed in the future. Even though it would not be possible to implement the particular characteristics of all crop varieties in a national-scale model, one interesting approach is to group cultivars by main characteristics. The Brazilian Agricultural Research Corporation regularly publishes guides with soybeans cultivar suitability for each region of the country, and even though it is not possible to know exactly where farmers apply each cultivar, these reports are an important guide on how the main cultivars are adapted to different environmental conditions across the territory.

BIBLIOGRAPHY

ANA (2013). *Conjuntura dos Recursos Hídricos no Brasil 2013*. Tech. rep. Brasilia: Agencia Nacional das Águas, p. 432. URL: http://conjuntura.ana.gov.br/docs/conj2014{_}inf.pdf.

– (2017). *Atlas Irrigação: uso da água na agricultura irrigada*. Tech. rep. Brasília: Agência Nacional de Águas, p. 86. URL: http://arquivos.ana.gov.br/imprensa/publicacoes/AtlasIrrigacao-UsodaAguanaAgriculturaIrrigada.pdf.

Abrahão, Gabriel M. and Marcos H. Costa (2018). "Evolution of rain and photoperiod limitations on the soybean growing season in Brazil: The rise (and possible fall) of double-cropping systems." In: *Agricultural and Forest Meteorology* 256-257.March, pp. 32–45. ISSN: 01681923. DOI: 10.1016/j.agrformet.2018.02.031.

Albuquerque, Monik Fernandes de (2013). "Medições e Modelagem da Pegada Hídrica da Cana-de-Açucar Cultivada no Brasil." Master Thesis. Universidade Federal de Campina Grande, p. 40. URL: http://www.scielo.br/pdf/rbeaa/v19n6/1415-4366-rbeaa-19-06-0521.pdf.

Allen, Richard, L.S. Pereira, D. Raes, and M. Smith (1998). "Crop evapotranspiration: Guidelines for computing crop requirements." In: *Irrigation and Drainage Paper No. 56, FAO* 56, p. 300. ISSN: 0254-5284. DOI: 10.1016/j.eja.2010.12.001.

Balkovič, Juraj, Rastislav Skalský, Christian Folberth, Nikolay Khabarov, Erwin Schmid, Mikuláš Madaras, Michael Obersteiner, and Marijn van der Velde (2018). "Impacts and Uncertainties of +2°C of Climate Change and Soil Degradation on European Crop Calorie Supply." In: *Earth's Future* 6.3, pp. 373–395. ISSN: 23284277. DOI: 10.1002/2017EF000629.

Balkovič, Juraj, Marijn van der Velde, Erwin Schmid, Rastislav Skalský, Nikolay Khabarov, Michael Obersteiner, Bernhard Stürmer, and Wei Xiong (2013). "Pan-European crop modelling with EPIC: Implementation, up-scaling and regional crop yield validation." In: *Agricultural Systems* 120, pp. 61–75. ISSN: 0308521X. DOI: 10.1016/j.agsy.2013.05.008.

Barretto, Alberto G.O.P., Göran Berndes, Gerd Sparovek, and Stefan Wirsenius (2013). "Agricultural intensification in Brazil and its effects on land-use patterns: An analysis of the 1975-2006 period." In: *Global Change Biology* 19.6, pp. 1804–1815. ISSN: 13541013. DOI: 10.1111/gcb.12174.

Biradar, Chandrashekhar M. and Xiangming Xiao (2011). "Quantifying the area and spatial distribution of double- and triple-cropping croplands in India with multi-temporal MODIS imagery in 2005." In: *International Journal of Remote Sensing* 32.2, pp. 367–386. ISSN: 13665901. DOI: 10.1080/01431160903464179.

Bleninger, Tobias and Luziadne Katiucia Kotsuka (2015). "Conceitos de água virtual e pegada hídrica: estudo de caso da soja e óleo de soja no Brasil." In: *Revista Recursos Hídricos* 36.1, pp. 15–24. ISSN: 08701741. DOI: 10.5894/rh36n1-2.

Bondeau, Alberte et al. (2007). "Modelling the role of agriculture for the 20th century global terrestrial carbon balance." In: *Global Change Biology* 13.3, pp. 679–706. ISSN: 1354-1013. DOI: 10.1111/j.1365-2486.2006.01305.x.

Carr, Joel A., Paolo D'Odorico, Francesco Laio, and Luca Ridolfi (2013). "Recent History and Geography of Virtual Water Trade." In: *PLoS ONE* 8.2, pp. 1–9. ISSN: 19326203. DOI: 10.1371/journal.pone.0055825.

Carvalho, André Luiz de and Rômulo Simões Cezar Menezes (2014). "Pegadas hídricas em sistemas agropecuários na região semiárida do Nordeste do Brasil." In: *Revista AgroAmbiente Online* 8.1, pp. 142–148.

Chapagain, A K and A Y Hoekstra (2003). "Virtual water trade: a quantification of virtual water flows between nations in relation to international trade of livestock and livestock products." In: *Virtual water trade proceedings of international expert meeting on virtual water trade - value of water* Research report series No.12, pp. 49–76.

Chapagain, Ashok K, a. Y. Hoekstra, and H. H. G. Savenije (2006). "Water saving through international trade of agricultural products." In: *Hydrology and Earth System Sciences* 10.3, pp. 455–468. ISSN: 1607-7938. DOI: 10.5194/hess-10-455-2006.

D'Odorico, Paolo et al. (2018). "The Global Food-Energy-Water Nexus." In: *Reviews of Geophysics*. ISSN: 87551209. DOI: 10.1029/2017RG000591.

D'Odorico, Paolo et al. (2019). "Global virtual water trade and the hydrological cycle: patterns, drivers, and socio-environmental impacts." In: *Environmental Research Letters* 14.5, p. 053001. ISSN: 1748-9326. DOI: 10.1088/1748-9326/ab05f4.

Davis, Kyle Frankel, Maria Cristina Rulli, Francesco Garrassino, Davide Chiarelli, Antonio Seveso, and Paolo D'Odorico (2017a). "Water limits to closing yield gaps." In: *Advances in Water Resources* 99, pp. 67–75. ISSN: 03091708. DOI: 10.1016/j.advwatres.2016.11.015.

Davis, Kyle Frankel, Maria Cristina Rulli, Antonio Seveso, and Paolo D'Odorico (2017b). "Increased food production and reduced water use through optimized crop distribution." In: *Nature Geoscience* 10.12, pp. 919–924. ISSN: 17520908. DOI: 10.1038/s41561-017-0004-5.

Dias, Lívia C.P., Fernando M. Pimenta, Ana B. Santos, Marcos H. Costa, and Richard J. Ladle (2016). "Patterns of land use, extensification, and intensification of Brazilian agriculture." In: *Global change biology* 22.8, pp. 2887–2903. ISSN: 13652486. DOI: 10.1111/gcb.13314.

Doell, Petra, Frank Kaspar, and Bernhard Lehner (Jan. 2003). "A global hydrological model for deriving water availability indicators: Model tuning and validation." In: *Journal of Hydrology* 270, pp. 105–134. DOI: 10.1016/S0022-1694(02)00283-4.

ESA (2017). *ESA: Land Cover CCI Product User Guide Version 2.0*. Tech. rep. URL: https://www.esa-landcover-cci.org/?q=node/163.

Erb, Karl-Heinz, Christian Lauk, Thomas Kastner, Andreas Mayer, Michaela C. Theurl, and Helmut Haberl (2016). "Exploring the biophysical option space for feeding the world without deforestation." In: *Nature Communications* 7.1, p. 11382. ISSN: 2041-1723. DOI: 10.1038/ncomms11382.

Fader, Marianela, D Gerten, M Thammer, J Heinke, W Lucht, and W Cramer (2011). "Internal and external green-blue agricultural water footprints of nations , and related water and land savings through trade." In: *Hydrology and Earth System Sciences* 15, pp. 1641–1660. DOI: 10.5194/hess-15-1641-2011.

Fader, Marianela, Stefanie Rost, Christoph Müller, Alberte Bondeau, and Dieter Gerten (2010). "Virtual water content of temperate cereals and maize: Present and potential future patterns." In: *Journal of Hydrology* 384.3-4, pp. 218–231. ISSN: 00221694. DOI: 10.1016/j.jhydrol.2009.12.011.

Falkenmark, M. and J. Rockstrom (2006). "The New Blue and Green Water Paradigm : Breaking New Ground for Water Resources Planning and Management." In: *Journal of Water Resource Planning Management* 132.June, pp. 129–132.

Falkenmark, Malin (1990). "Global Water Issues Confronting Humanity." In: *Journal of Peace Research* 27.2, pp. 177–190. DOI: 10.1177/002234339002700200 7.

Falkenmark, Malin and David Molden (2008). "Wake Up to Realities of River Basin Closure." In: *International Journal of Water Resources Development* 24.2, pp. 201–215. DOI: 10.1080/07900620701723570.

Falkenmark, Malin and Johan Rockström (2010). "Building water resilience in the face of global change: from a blue-only to a green-blue water approach to land-water management." In: *Journal of Water Resources Planning and Management* December, pp. 606–611.

Flach, Rafaela, Ylva Ran, Javier Godar, Louise Karlberg, and Clement Suavet (2016). "Towards more spatially explicit assessments of virtual water flows: linking local water use and scarcity to global demand of Brazilian farming commodities." In: *Environmental Research Letters* 11.7, p. 075003. ISSN: 1748-9326. DOI: 10.1088/1748-9326/11/7/075003.

Folberth, Christian, Thomas Gaiser, Karim C. Abbaspour, Rainer Schulin, and Hong Yang (2012). "Regionalization of a large-scale crop growth model for sub-Saharan Africa: Model setup, evaluation, and estimation of maize yields." In: *Agriculture, Ecosystems and Environment* 151, pp. 21–33. ISSN: 01678809. DOI: 10.1016/j.agee.2012.01.026.

Foley, J. A. (2005). "Global Consequences of Land Use." In: *Science* 309.5734, pp. 570–574. ISSN: 0036-8075. DOI: 10.1126/science.1111772. arXiv: arXiv:1011.1669v3.

Foley, Jonathan A. et al. (2011). "Solutions for a cultivated planet." In: *Nature* 478.7369, pp. 337–342. ISSN: 00280836. DOI: 10.1038/nature10452. arXiv: 9605103 [cs].

Gassman, Pw and Jr Williams (2009). *The Agricultural Policy Environmental Extender (APEX) model: An emerging tool for landscape and watershed environmental analyses*. Tech. rep. Ames, Iowa: Center for Agricultural and Rural Development Iowa State University. DOI: 10.13031/2013.30078. URL: http://www.public.iastate.edu/{~}marks/apexreviewreportsc-edit(draftCARDreport).doc.

Gerten, D., J. Heinke, H. Hoff, H. Biemans, M. Fader, and K. Waha (2011). "Global Water Availability and Requirements for Future Food Production." In: *Journal of Hydrometeorology* 12.5, pp. 885–899. ISSN: 1525-755X. DOI: 10.1175/2011JHM1328.1.

Gerten, Dieter et al. (2013). "Towards a revised planetary boundary for consumptive freshwater use: role of environmental flow requirements." In: *Current Opinion in Environmental Sustainability* 5.6, pp. 551–558. ISSN: 18773435. DOI: 10.1016/j.cosust.2013.11.001.

Gibbs, H. K., A. S. Ruesch, F. Achard, M. K. Clayton, P. Holmgren, N. Ramankutty, and J. A. Foley (2010). "Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s." In: *Proceedings of the National Academy of Sciences* 107.38, pp. 16732–16737. ISSN: 0027-8424. DOI: 10.1073/pnas.0910275107.

Gleick, P. H. and M. Palaniappan (2010). "Peak water limits to freshwater withdrawal and use." In: *Proceedings of the National Academy of Sciences* 107.25, pp. 11155–11162. ISSN: 0027-8424. DOI: 10.1073/pnas.1004812107.

Godar, Javier, U. Martin Persson, Emilio Jorge Tizado, and Patrick Meyfroidt (2015). "Towards more accurate and policy relevant footprint analyses: Tracing fine-scale socio-environmental impacts of production to consumption." In: *Ecological Economics* 112, pp. 25–35. ISSN: 09218009. DOI: 10.1016/j.ecolecon.2015.02.003.

Gordon, Line J., Will Steffen, Bror F. Jönsson, Carl Folke, Malin Falkenmark, and Åse Johannessen (2005). "Human modification of global water vapor flows from the land surface." In: *Proceedings of the National Academy of Sciences of the United States of America* 102.21, pp. 7612–7617. ISSN: 00278424. DOI: 10.1073/pnas.0500208102.

Guilpart, Nicolas, Patricio Grassini, Victor O. Sadras, Jagadish Timsina, and Kenneth G. Cassman (2017). "Estimating yield gaps at the cropping system level." In: *Field Crops Research* 206, pp. 21–32. ISSN: 03784290. DOI: 10.1016/j.fcr.2017.02.008.

Hanasaki, N., S. Kanae, T. Oki, K. Masuda, K. Motoya, N. Shirakawa, Y. Shen, and K. Tanaka (2008). "An integrated model for the assessment of global water resources - Part 1: Model description and input meteorological forcing." In: *Hydrology and Earth System Sciences* 12.4, pp. 1007–1025. ISSN: 16077938. DOI: 10.5194/hess-12-1007-2008.

Hanasaki, Naota, Toshiyuki Inuzuka, Shinjiro Kanae, and Taikan Oki (2010). "An estimation of global virtual water flow and sources of water withdrawal for major crops and livestock products using a global hydrological model." In: *Journal of Hydrology* 384.3-4, pp. 232–244. ISSN: 00221694. DOI: 10.1016/j.jhydrol.2009.09.028.

Hansen, J. W. and J. W. Jones (2000). "Short Survey: Scaling-up crop models for climate variability." In: *Agricultural Systems* 65.1, pp. 43–72. ISSN: 0308521X. DOI: 10.1016/S0308-521X(00)00025-1.

Hengl, Tomislav et al. (2014). "SoilGrids1km — Global Soil Information Based on Automated Mapping." In: *PLoS ONE* 9.8. Ed. by Ben Bond-Lamberty, e105992. ISSN: 1932-6203. DOI: 10.1371/journal.pone.0105992.

Hoekstra, Arjen Y, Ashok K Chapagain, Maite M Aldaya, and Mesfin M Mekonnen (2011). *The Water Footprint Assessment Manual: Setting the Global Standard*. London, UK: Routledge. ISBN: 9781849712798.

Hoff, H., M. Falkenmark, D. Gerten, L.J. Gordon, L. Karlberg, and J. Rockström (2010). "Greening the global water system." In: *Journal of Hydrology* 384.3-4, pp. 177–186. ISSN: 00221694. DOI: 10.1016/j.jhydrol.2009.06.026.

IBGE (Brazilian Institute of Geography and Statistics) (2018). *Levantamento Sistemático da Produção Agrícola*. URL: https://sidra.ibge.gov.br/tabela/6588 (visited on 12/13/2018).

IPBES (2019). *Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Tech. rep. IPBES. URL: https://www.ipbes.net/sites/default/files/downloads/spm_unedited_advance_for_posting_htn.pdf.

IPCC (2019). *Climate Change and Land - Summary for Policymakers*. Tech. rep. IPCC. URL: https://www.ipcc.ch/srccl-report-download-page/.

J. R. Williams, C. A. Jones, J. R. Kiniry, and D. A. Spanel (1989). "The EPIC Crop Growth Model." In: *Transactions of the ASAE* 32.2, pp. 0497–0511. DOI: 10.13031/2013.31032.

Jägermeyr, J., D. Gerten, J. Heinke, S. Schaphoff, M. Kummu, and W. Lucht (2015). "Water savings potentials of irrigation systems: global simulation of processes and linkages." In: *Hydrology and Earth System Sciences* 19.7, pp. 3073–3091. ISSN: 1607-7938. DOI: 10.5194/hess-19-3073-2015.

Jarvis, A., H.I. Reuter, A. Nelson, and E. Guevara (2008). *Hole-filled SRTM for the globe Version 4, available from the CGIAR-CSI SRTM 90m Database.* Tech. rep. CGIAR. URL: http://srtm.csi.cgiar.org.

Jones, James W. et al. (2017). "Brief history of agricultural systems modeling." In: *Agricultural Systems* 155, pp. 240–254. ISSN: 0308521X. DOI: 10.1016/j.agsy.2016.05.014.

Keys, Patrick W. and Lan Wang-Erlandsson (2018). "On the social dynamics of moisture recycling." In: *Earth System Dynamics* 9.2, pp. 829–847. ISSN: 21904987. DOI: 10.5194/esd-9-829-2018.

Keys, Patrick W., Lan Wang-Erlandsson, and Line J. Gordon (2016). "Revealing Invisible Water: Moisture Recycling as an Ecosystem Service." In: *PLOS ONE* 11.3. Ed. by Gary Stuart Bilotta, e0151993. ISSN: 1932-6203. DOI: 10.1371/journal.pone.0151993.

Kissinger, Gabrielle, Martin Herold, and Veronique de Sy (2012). *Drivers of Deforestation and Forest Degradation: A Synthesis Report for REDD+ Policymakers.* Tech. rep. Vancouver, Canada: Lexeme Consult. URL: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/65505/6316-drivers-deforestation-report.pdf.

Konar, M., Z. Hussein, Naota Hanasaki, D. L. Mauzerall, and I. Rodriguez-Iturbe (2013). "Virtual water trade flows and savings under climate change." In: *Hydrology and Earth System Sciences* 17, pp. 3219–3234. ISSN: 10275606. DOI: 10.5194/hess-17-3219-2013.

Lathuillière, Michael J., Cécile Bulle, and Mark S. Johnson (2018). "A contribution to harmonize water footprint assessments." In: *Global Environmental Change* 53.December 2017, pp. 252–264. ISSN: 09593780. DOI: 10.1016/j.gloenvcha.2018.10.004.

Lathuillière, Michael J., Michael T. Coe, and Mark S. Johnson (2016). "A review of green-and blue-water resources and their trade-offs for future agricultural production in the Amazon Basin: What could irrigated agriculture mean for Amazonia?" In: *Hydrology and Earth System Sciences* 20.6, pp. 2179–2194. ISSN: 16077938. DOI: 10.5194/hess-20-2179-2016.

Lathuillière, Michael J., Higo J. Dalmagro, T. Andrew Black, Paulo H.Z.de Arruda, Iain Hawthorne, Eduardo G. Couto, and Mark S. Johnson (2018a). "Rainfed and irrigated cropland-atmosphere water fluxes and their implications for agricultural production in Southern Amazonia." In: *Agricultural and Forest Meteorology* 256-257.October 2017, pp. 407–419. ISSN: 01681923. DOI: 10.1016/j.agrformet.2018.03.023.

Lathuillière, Michael J., Mark S. Johnson, and Simon D. Donner (2012). "Water use by terrestrial ecosystems: Temporal variability in rainforest and agricultural contributions to evapotranspiration in Mato Grosso, Brazil." In: *Environmental Research Letters* 7.2. ISSN: 17489326. DOI: 10.1088/1748-9326/7/2/024024.

Lathuillière, Michael J, Mark S Johnson, Gillian L Galford, and Eduardo G Couto (2014). "Environmental footprints show China and Europe's evolving resource appropriation for soybean production in Mato Grosso, Brazil." In: *Environmental Research Letters* 9.7, p. 074001. ISSN: 1748-9326. DOI: 10.1088/1748-9326/9/7/074001.

Lathuillière, Michael, Michael Coe, Andrea Castanho, Jordan Graesser, and Mark Johnson (2018b). "Evaluating Water Use for Agricultural Intensification in Southern Amazonia Using the Water Footprint Sustainability Assessment." In: *Water* 10.4, p. 349. ISSN: 2073-4441. DOI: 10.3390/w10040349.

Liu, J., A.J.B. Zehnder, and H. Yang (2008). "Drops for Crops: Modelling Crop Water Productivity on a Global Scale." In: *Global NEST Journal* 10.3, pp. 295–300.

Liu, Junguo (2009). "A GIS-based tool for modelling large-scale crop-water relations." In: *Environmental Modelling and Software* 24.3, pp. 411–422. ISSN: 13648152. DOI: 10.1016/j.envsoft.2008.08.004.

Liu, Junguo, Jimmy R. Williams, Alexander J.B. Zehnder, and Hong Yang (2007). "GEPIC – modelling wheat yield and crop water productivity with high resolution on a global scale." In: *Agricultural Systems* 94.2, pp. 478–493. ISSN: 0308521X. DOI: 10.1016/j.agsy.2006.11.019.

Liu, Junguo and Hong Yang (2010). "Spatially explicit assessment of global consumptive water uses in cropland: Green and blue water." In: *Journal of Hydrology* 384.3-4, pp. 187–197. ISSN: 00221694. DOI: 10.1016/j.jhydrol.2009.11.024.

Mekonnen, M. M. and a. Y. Hoekstra (2011). "The green, blue and grey water footprint of crops and derived crop products." In: *Hydrology and Earth System Sciences* 15.5, pp. 1577–1600. ISSN: 1607-7938. DOI: 10.5194/hess-15-1577-2011.

Mueller, Nathaniel D., James S. Gerber, Matt Johnston, Deepak K. Ray, Navin Ramankutty, and Jonathan A. Foley (2012). "Closing yield gaps through nutrient and water management." In: *Nature* 490.7419, pp. 254–257. ISSN: 00280836. DOI: 10.1038/nature11420. arXiv: NIHMS150003.

Niu, Xianzeng, William Easterling, Cynthia J. Hays, Allyson Jacobs, and Linda Mearns (2009). "Reliability and input-data induced uncertainty of the EPIC model to estimate climate change impact on sorghum yields in the U.S. Great Plains." In: *Agriculture, Ecosystems and Environment* 129.1-3, pp. 268–276. ISSN: 01678809. DOI: 10.1016/j.agee.2008.09.012.

Nobre, Antonio Donato (2014). *The Future Climate of Amazonia - Scientific Assessment Report*. Tech. rep. São José dos Campos, SP: CCST-INPE:INPA.

Philip W. Gassman, Jimmy R. Williams, Verel W. Benson, R. Cesar Izaurralde, Larry M. Hauck, C. Allan Jones, Jay D. Atwood, James R. Kiniry, and Joan D. Flowers (2004). "Historical Development and Applications of the EPIC and APEX models." In: *2004, Ottawa, Canada August 1 - 4, 2004*. St. Joseph, MI: American Society of Agricultural and Biological Engineers, p. 31. ISBN: Working Paper 05-WP 397. DOI: 10.13031/2013.17074. URL: https://lib.dr.iastate.edu/card_workingpapers/422/.

Portmann, Felix T., Stefan Siebert, and Petra Döll (2010). "MIRCA2000-Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling." In: *Global Biogeochemical Cycles* 24.1, n/a–n/a. DOI: 10.1029/2008gb003435.

Quinteiro, Paula, Ana Cláudia Dias, Margarida Silva, Bradley G. Ridoutt, and Luís Arroja (2015). “A contribution to the environmental impact assessment of green water flows.” In: *Journal of Cleaner Production* 93, pp. 318–329. ISSN: 09596526. DOI: 10.1016/j.jclepro.2015.01.022.

Ramankutty, Navin, Zia Mehrabi, Katharina Waha, Larissa Jarvis, Claire Kremen, Mario Herrero, and Loren H. Rieseberg (2018). “Trends in Global Agricultural Land Use: Implications for Environmental Health and Food Security.” In: *Annual Review of Plant Biology* 69.1. ISSN: 1543-5008. DOI: 10.1146/annurev-arplant-042817-040256.

Ray, Deepak K. and Jonathan A. Foley (2013). “Increasing global crop harvest frequency: Recent trends and future directions.” In: *Environmental Research Letters* 8.4. ISSN: 17489326. DOI: 10.1088/1748-9326/8/4/044041.

Ridoutt, Bradley G. and Stephan Pfister (2010). “A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity.” In: *Global Environmental Change* 20, pp. 113–120. ISSN: 09593780. DOI: 10.1016/j.gloenvcha.2009.08.003.

Rockström, Johan, Malin Falkenmark, Carl Folke, Mats Lannerstad, Jennie Barron, Elin Enfors, Line Gordon, Jens Heinke, Holger Hoff, and Claudia Pahl-Wostl (2014). *Water Resilience for Human Prosperity*. Cambridge University Press, p. 311. ISBN: 9781107024199.

Rockström, Johan, Malin Falkenmark, Louise Karlberg, Holger Hoff, Stefanie Rost, and Dieter Gerten (2009). “Future water availability for global food production: The potential of green water for increasing resilience to global change.” In: *Water Resources Research* 45.7, pp. 1–16. ISSN: 00431397. DOI: 10.1029/2007WR006767.

Rosa, Lorenzo, Maria Cristina Rulli, Kyle Frankel Davis, Davide Danilo Chiarelli, Corrado Passera, and Paolo D’Odorico (2018). “Closing the yield gap while ensuring water sustainability.” In: *Environmental Research Letters*. ISSN: 1748-9326. DOI: 10.1088/1748-9326/aadeef.

Rost, S, D Gerten, and U Heyder (2008). “Human alterations of the terrestrial water cycle through land management.” In: *Advances in Geosciences* 18, pp. 43–50. ISSN: 00431397. DOI: 10.5194/adgeo-18-43-2008.

Rost, Stefanie, Dieter Gerten, Holger Hoff, Wolfgang Lucht, Malin Falkenmark, and Johan Rockström (2009). “Global potential to increase crop production through water management in rainfed agriculture.” In: *Environmental Research Letters* 4.4. ISSN: 17489326. DOI: 10.1088/1748-9326/4/4/044002.

Rudorff, Bernardo Friedrich Theodor, Daniel Alves de Aguiar, Wagner Fernando da Silva, Luciana Miura Sugawara, Marcos Adami, and Mauricio Alves Moreira (2010). “Studies on the rapid expansion of sugarcane for ethanol production in São Paulo state (Brazil) using Landsat data.” In: *Remote Sensing* 2.4, pp. 1057–1076. ISSN: 20724292. DOI: 10.3390/rs2041057.

Sacks, William J., Delphine Deryng, Jonathan A. Foley, and Navin Ramankutty (2010). “Crop planting dates: An analysis of global patterns.” In: *Global Ecology and Biogeography* 19.5, pp. 607–620. ISSN: 1466822X. DOI: 10.1111/j.1466-8238.2010.00551.x.

Schyns, Joep F, Arjen Y Hoekstra, Martijn J Booij, Rick J Hogeboom, and Mesfin M Mekonnen (2019). “Limits to the world’s green water resources for food, feed, fiber, timber, and bioenergy.” In: *Proceedings of the National Academy of Sciences* 116.11, pp. 4893–4898. ISSN: 0027-8424. DOI: 10.1073/pnas.1817380116.

Siad, Si Mokrane, Vito Iacobellis, Pandi Zdruli, Andrea Gioia, Ilan Stavi, and Gerrit Hoogenboom (2019). "A review of coupled hydrologic and crop growth models." In: *Agricultural Water Management* 224.June, p. 105746. ISSN: 03783774. DOI: 10.1016/j.agwat.2019.105746.

Siebert, Stefan and Petra Döll (2008). *The Global Crop Water Model (GCWM): Documentation and first results for irrigated crops*. Tech. rep. March. Frankfurt am Main, Germany: Frankfurt am Main University. URL: http://publikationen.stub.uni-frankfurt.de/frontdoor/index/index/docId/81.

– (2010). "Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation." In: *Journal of Hydrology* 384.3-4, pp. 198–217. ISSN: 00221694. DOI: 10.1016/j.jhydrol.2009.07.031.

Silva, Vicente de Paulo R. da et al. (2016b). "Water footprint and virtual water trade of brazil." In: *Water (Switzerland)* 8.11. ISSN: 20734441. DOI: 10.3390/w8110517.

Skalský, Rastislav, Zuzana Tarasovičová, Juraj Balkovič, Erwin Schmid, Michael Fuchs, Elena Moltchanova, Georg Kindermann, and Peter Scholtz (2008). *GEO-BENE global database for bio-physical modeling v. 1.0*. Tech. rep. Laxenburg, Austria: International Institute for Applied Systems Analysis (IIASA), p. 58.

Smith, Martin (1992). *CROPWAT: A computer program for irrigation planning and management*. 46. Food & Agriculture Org.

Spera, Stephanie A., Avery S. Cohn, Leah K. Vanwey, Jack F. Mustard, Bernardo F. Rudorff, Joel Risso, and Marcos Adami (2014). "Recent cropping frequency, expansion, and abandonment in Mato Grosso, Brazil had selective land characteristics." In: *Environmental Research Letters* 9.6. ISSN: 17489326. DOI: 10.1088/1748-9326/9/6/064010.

Tuninetti, Marta, Stefania Tamea, Paolo D'Odorico, Francesco Laio, and Luca Ridolfi (2015). "Global sensitivity of high-resolution estimates of crop water footprint." In: *Water Resources Research* 51.10, pp. 8257–8272. ISSN: 19447973. DOI: 10.1002/2015WR017148.

Usubiaga-Liaño, Arkaitz, Georgina M. Mace, and Paul Ekins (2019). "Limits to agricultural land for retaining acceptable levels of local biodiversity." In: *Nature Sustainability* 2.6, pp. 491–498. ISSN: 2398-9629. DOI: 10.1038/s41893-019-0300-8.

Vörösmarty, C J and Dork Sahagian (2000). "Anthropogenic Disturbance of the Terrestrial Water Cycle." In: *BioScience* 50.9, pp. 753–765.

Wada, Yoshihide and Marc F P Bierkens (2014). "Sustainability of global water use: past reconstruction and future projections." In: *Environmental Research Letters* 9.10, p. 104003. ISSN: 1748-9326. DOI: 10.1088/1748-9326/9/10/104003.

Waha, K., L. G.J. Van Bussel, C. Müller, and A. Bondeau (2012). "Climate-driven simulation of global crop sowing dates." In: *Global Ecology and Biogeography* 21.2, pp. 247–259. ISSN: 1466822X. DOI: 10.1111/j.1466-8238.2011.00678.x.

Wang, X. et al. (2012). "EPIC and APEX: Model use, calibration, and validation." In: *Transactions of the American Society of Agricultural and Biological Engineers* 55.1996, pp. 1447–1462. ISSN: 2151-0032. DOI: 10.13031/2013.42253.

Wartenburger, Richard et al. (2018). "Evapotranspiration simulations in ISIMIP2a — Evaluation of spatio-temporal characteristics with a comprehensive en-

semble of independent datasets." In: *Environmental Research Letters* 13.7, p. 075001. ISSN: 1748-9326. DOI: 10.1088/1748-9326/aac4bb.
Williams, J. R., S. Dagitz, M. Margre, A. Meinardus, E. Steglich, and R. Taylor (2015). *EPIC: Environmental Policy Integrated Climate Model User's Manual Version 0810*. Tech. rep. September. Temple, Tx. URL: http://epicapex.tamu.edu/files.
Williams, J. W., R.C. Izaurralde, and E. M. Steglich (2008). *Agricultural Policy/Environmental eXtender theoretical documentation*. Tech. rep. June. Temple, Texas: Blackland Research and Extension Center, p. 131.
Wisser, Dominik, Steve Frolking, Ellen M. Douglas, Balazs M. Fekete, Andreas H. Schumann, and Charles J. Vörösmarty (2010). "The significance of local water resources captured in small reservoirs for crop production - A global-scale analysis." In: *Journal of Hydrology* 384.3-4, pp. 264–275. ISSN: 00221694. DOI: 10.1016/j.jhydrol.2009.07.032.
Wu, Wenbin, Qiangyi Yu, Liangzhi You, Kevin Chen, Huajun Tang, and Jianguo Liu (2018). "Global cropping intensity gaps: Increasing food production without cropland expansion." In: *Land Use Policy* 76.February, pp. 515–525. ISSN: 02648377. DOI: 10.1016/j.landusepol.2018.02.032.
Xavier, Alexandre C., Carey W. King, and Bridget R. Scanlon (2016). "Daily gridded meteorological variables in Brazil (1980-2013)." In: *International Journal of Climatology* 36.6, pp. 2644–2659. ISSN: 08998418. DOI: 10.1002/joc.4518. arXiv: 1311.1716.
Yan, Huimin, Xiangming Xiao, Heqing Huang, Jiyuan Liu, Jingqing Chen, and Xuehong Bai (2014). "Multiple cropping intensity in China derived from agrometeorological observations and MODIS data." In: *Chinese Geographical Science* 24.2, pp. 205–219. ISSN: 1993064X. DOI: 10.1007/s11769-013-0637-2.
Zalles, Viviana et al. (2019). "Near doubling of Brazil's intensive row crop area since 2000." In: *Proceedings of the National Academy of Sciences* 116.2, pp. 428–435. ISSN: 0027-8424. DOI: 10.1073/pnas.1810301115.
Zhao, Yan, Linyan Bai, Jianzhong Feng, Xiaosong Lin, Li Wang, Lijun Xu, Qiyun Ran, and Kui Wang (2016). "Spatial and Temporal Distribution of Multiple Cropping Indices in the North China Plain Using a Long Remote Sensing Data Time Series." In: *Sensors* 16.4, p. 557. ISSN: 1424-8220. DOI: 10.3390/s16040557.

ARTICLES

2

WATER PRODUCTIVITY AND FOOTPRINT OF MAJOR BRAZILIAN RAINFED CROPS – A SPATIALLY EXPLICIT ANALYSIS OF CROP MANAGEMENT SCENARIOS

After peer-review, the following chapter has been published with modifications as:

Flach, R., Skalský, R., Folberth, C., Balkovič, J., Jantke, K., Schneider, U.A., 2020. "Water productivity and footprint of major Brazilian rainfed crops – A spatially explicit analysis of crop management scenarios." *Agric. Water Manag.* **233**, 105996. https://doi.org/10.1016/j.agwat.2019.105996

The processed input and results related to this paper are available as open data as:

Flach, Rafaela. (2019). Water productivity and footprint of major Brazilian rainfed crops – a spatially-explicit analysis of crop management scenarios. *Max Planck Society*. https://dx.doi.org/10.17617/3.27

Rafaela Flach (R.F.) and the other co-authors contributed to the paper as follows: R.F. planned and carried out the model simulations. U.S. and K.J supervised the design of this research work and the interpretation of its findings. R.S., C.F. and J.B. provided fundamental guidance on the technical aspects of the model, contributed to the calibration and validation of the model, and supervised the result analysis. In particular, R.S. supervised the model parameter adjustments, while C.F. made modifications on the model source code to make it suitable for application in the southern hemisphere. R.F. analyzed the data and developed the approach for analysis of the presented results. R.F took the lead in writing the manuscript, while all other co-authors provided critical feedback on the manuscript and helped to finalize this publication.

The authors acknowledge the kind contribution of Dr. Mauricio Antonio Lopes, the former president of the Brazilian Agricultural Research Corporation (EMBRAPA). Dr. Lopes performed a pre-submission review and provided valuable feedback, which greatly improved this manuscript.

Water productivity and footprint of major Brazilian rainfed crops – a spatially explicit analysis of crop management scenarios

Rafaela Flach[1,2], Rastislav Skalský[3,4], Christian Folberth[3], Juraj Balkovič[3,5], Kerstin Jantke[1,6], Uwe Schneider[1,6]

[1] Research Unit Sustainability and Global Change, Universität Hamburg, Grindelberg 5, 20144 Hamburg, Germany.
[2] International Max Planck Research School on Earth System Modelling (IMPRS-ESM), Max Planck Institute for Meteorology, Bundesstr. 53, 20146 Hamburg, Germany.
[3] International Institute for Applied Systems Analysis, Ecosystem Services and Management Program, Schlossplatz 1, A-2361 Laxenburg, Austria
[4] National Agricultural and Food Centre, Soil Science and Conservation Research Institute, Trenčianska 55, 824 80 Bratislava, Slovak Republic
[5] Department of Soil Science, Faculty of Natural Sciences, Comenius University in Bratislava, Ilkovičova 6, 842 15 Bratislava, Slovak Republic
[6] Center for Earth System Research and Sustainability (CEN), Universität Hamburg, Bundesstr. 53, 20146 Hamburg, Germany.

ABSTRACT

Green water is a central resource for global agricultural production. Therefore, understanding its role is fundamental to design strategies to increase global food and feed production, while avoiding further land conversion, and obtaining more crop per drop. Brazil is a country with high water availability, and a major exporter of agricultural goods and virtual water. We assess here water use and water productivity in Brazil for four major rainfed crops: cotton, maize, soybeans, and wheat. For this, we used the EPIC crop model to perform a spatially explicit assessment of consumptive water use and water productivity under crop management scenarios in Brazil between 1990 and 2013. We investigated four different land-water interactions: (i) water use and productivity for different management scenarios, (ii) the prospective role of supplemental irrigation for productivity improvement, (iii) changes in green water use throughout the study period, and finally (iv) land and water savings related to agricultural intensification. The results show that, for the studied crops, green water is the main resource for food production, and intensification can lead to great improvements in green water productivity. The results also suggest that, despite resulting in higher yields, irrigated intensification tends to result in lower overall water productivity, compared to fertilizer-based intensification strategies. This is, however, regionally and crop-specific. Furthermore, closing the yield gap through irrigated or rainfed intensification enables to reduce resource demand, in the order of 34-58% for cropland, and 29-52% for water.

Keywords: Green Water; Sustainability; Yield Gap; EPIC; Crop Modeling; Water Footprint

2.1 introduction

Increasing demands for food, feed, and bioenergy are a major challenge for sustainable water use in the coming decades. Human activities have already overused blue water sources (i.e. liquid water in rivers, lakes, wetlands, and aquifers) worldwide (Falkenmark and Molden, 2008; Vörösmarty and Sahagian, 2000; Wada and Bierkens, 2014). Blue water scarcity limits the potential productivity of agricultural systems (Davis et al., 2017a). On the other side, green water use (i.e. soil water formed by precipitation and available to plants) is about 4 to 5 times higher than blue water use in agriculture globally (Hoff et al., 2010). While water science has mostly focused on estimating and managing blue water,understanding how to make better use of green water resources is fundamental to meet future demands (Falkenmark and Rockstrom, 2006).

Improvement of water productivity, usually defined as the amount of crop obtained relative to the evapotranspiration sourced from green and blue water during production, has been identified as a viable strategy to reduce the need for additional resources in irrigated and rainfed systems (Molden et al., 2010). On a large scale, trade from areas with high to those of low water productivity levels results in net water savings (Chapagain, Hoekstra, and Savenije, 2006; Fader et al., 2011). Improving the management of green water, and increasing green water productivity, is fundamental both in arid and water-abundant areas (Rockström and Barron, 2007). Higher crop yields have the potential to reduce the impact of agricultural systems by facilitating sparing of lands with high biodiversity (Phalan et al., 2011). At the same time, obtaining more crop per drop also has the potential to generate net water savings and reduce pressure in regions with higher water stress or scarcity (Fader et al., 2011).

Traditionally, water footprint studies have largely focused on impacts of water use on the location of production, and particularly on water-stressed areas. Brazil has abundant blue and green water resources, although the local availability of water is highly heterogeneous (ANA, 2013; Flach et al., 2016). As a major agricultural producer and net exporter of agricultural commodities, Brazil exports around 54.8 billion m^3 of virtual water per year, mainly to Europe (Silva et al., 2016a). Brazilian agriculture has undergone stark changes in the last decades, through horizontal expansion and intensification (Dias et al., 2016; Zalles et al., 2019). The expansion of Brazilian cropland has been connected to increasing conversion of natural ecosystems, and negative impacts to biodiversity and the water cycle (Bondeau et al., 2007; Gibbs et al., 2010; Spera et al., 2016; Zalles et al., 2019).

Previous virtual water trade analysis of Brazilian agriculture on a national scale relied on datasets from previous global water footprint assessments, such as the one presented in the work of Mekonnen and Hoekstra (2011) (Flach et al., 2016; Silva et al., 2016a). Other water footprint and virtual water trade studies focused on smaller scale, and relied on local measurements (Albuquerque, 2013; Carvalho and Menezes, 2014; Silva et al., 2016b) or combined those with satellite data (Lathuillière et al., 2014; Lathuillière et al., 2018b).

This is one of the first studies to model local agricultural water footprints for Brazilian agriculture at a national scale. Our main contribution is a large-scale and locally relevant water use analysis with high spatial-explicitness and updated input data. We analyze land and water interactions for agricultural production in the recent past, and for scenarios of agricultural management. We aim to understand the recent changes in green water use in Brazilian agriculture, but also possibilities for the future.

By providing spatially explicit and process-based assessments of green and blue water in agriculture, advanced crop models have enabled the progress of global water footprints and trade studies. These biophysical models applied in global water assessments include GEPIC (Liu and Yang, 2010; Liu, Zehnder, and Yang, 2009), GCWM (Siebert and Döll, 2008), H08 (Hanasaki et al., 2013; Konar et al., 2016), LPJmL (Fader et al., 2010; Gerten et al., 2011; Rost, Gerten, and Heyder, 2008), and WBMplus (Wisser et al., 2008). With the use of the EPIC biophysical crop model and high resolution soil, elevation and climate data, we simulated 24 crop cycles between 1990 and 2013 for four traditionally rainfed crops: cotton, first and second season maize, soybeans, and wheat.

This paper is structured as follows. We document our modelling approach in section 2, and data in section 3. We present the model results in section 4. First, we analyze how changes in nutrient input affect yields and water productivity, and investigate how the intensification of food production in Brazil affects agricultural water use efficiency. Furthermore, we estimate the geographical distribution of irrigation potential across the country. Lastly, we analyzed the influence of agricultural intensification scenarios on the demand for water and land. The results are discussed in the section 5.

2.2 MATERIALS AND METHODS

2.2.1 *Study area and simulation units*

We focused on four of Brazil's most important crops regarding consumptive water use and production: cotton, maize, soybeans, and wheat. These four crops are among the ten most important crops in terms of harvested area and total production in Brazil. They covered approximately 70% of the total harvested area in Brazil in 2017 (IBGE (Brazilian Institute of Geography and Statistics), 2018), and are predominantly produced in rainfed systems (ANA, 2017). We modeled maize twice, to represent two production systems: the main maize crop, and second maize crop, called safrinha in Brazil. Brazilian farmers commonly plant safrinha maize as a second crop after soybeans, and therefore second season maize has a different calendar from main season maize. Our model setup does not simulate double-cropping, and instead simulates second season maize separately, as a fifth crop. The yield of maize, soybeans and wheat correspond to the seed yield, while the cotton yield corresponds to both the lint and seed yields.

We simulated soil and water processes associated with crop growth in Brazil between 1990 and 2013. The simulated area comprises only areas classified as cropland during the study period (see Figure 2.1).

For this study, the EPIC model was setup and run for more than 8.10^4 simulation units. These units were classified primarily in terms of their biophysical homogeneity, and then further delimited based on municipality administrative boundaries. The procedure for delimitation of the simulation units was adapted from the methodology developed for the GEOBENE global database for bio-physical modeling (Skalský et al., 2008). First, a homogeneous response unit (HRU) is considered an area with similar soil, topography and climate characteristics. For delimitation of the HRUs, we classified the soil and topography databases based on predetermined thresholds (see detailed description and thresholds in Section A.1.1). The final boundaries of the simulation units resulted from the overlap of the climate dataset grid, the municipality boundaries, and the boundaries of the previously delimited HRUs. The resolution of the datasets used to delimitate the simulation units ranged from the 300m resolution land use maps (ESA, 2017), 1 km resolution soil and topography datasets (Hengl et al., 2014; Jarvis et al., 2008), and the 0.25 degrees climate grid (Xavier, King, and Scanlon, 2016). The municipal boundary shapefile divides the Brazilian territory in approximately 6000 municipalities.

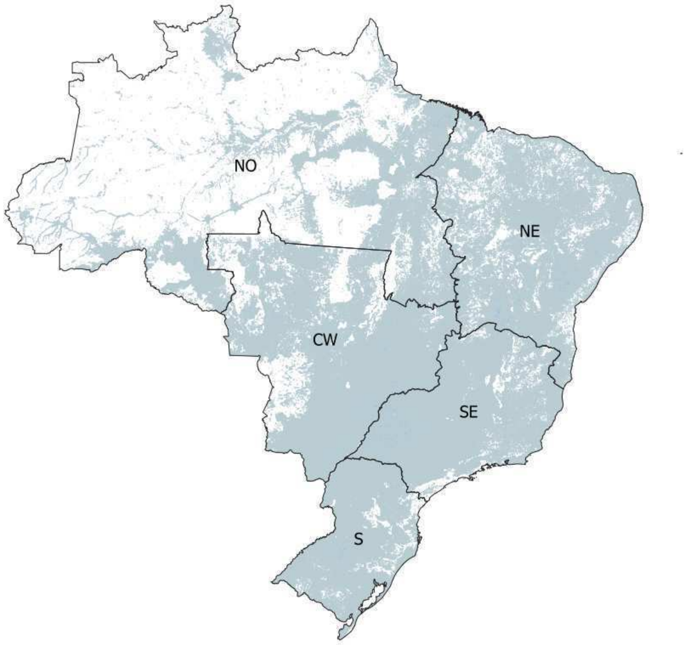


Figure 2.1: Simulation units (shaded area) in the five Brazilian administrative regions (NO: North, NE: Northeast, SE: Southeast, S: South, CW: Center-West).

2.2.2 *General crop model characteristics*

The Environmental Policy Integrated Climate (EPIC) model simulates the biological, physical and chemical processes that occur in the soil-plant-atmosphere-management system (Williams, Izaurralde, and Steglich, 2008). EPIC operates in daily time steps, and has no spatial component. The model contains sub-components, which simulate processes related to weather, hydrology, erosion, nutrients, soil temperature, plant growth, plant environment control, and tillage. Although originally designed to model soil erosion, EPIC has been used comprehensively to simulate climate change impacts, nutrient cycling and loss, soil carbon, pesticide fate, among others (Philip W. Gassman et al., 2004).

Spatially explicit implementations of the EPIC model have been applied earlier to study impacts of crop management on yields and externalities across a range of management systems ranging from smallholder agriculture (Folberth et al., 2012) to high-input systems (Balkovič et al., 2014) and has frequently been used to study crop-water relations (Liu et al., 2007; Liu and Yang, 2010; Liu, Zehnder, and Yang, 2009). The model has been evaluated positively across scales from the field (e.g. Williams et al., 1995) to continental (Balkovič et al., 2018; Folberth et al., 2012) and global assessments (Müller et al., 2017).

Here the 0810 version of the model source code in FORTRAN was compiled and modified for parallel processing in a Linux environment, to make it capable of iterative simulations over a large number of parameter settings.

2.2.3 *Simulation setup*

To reduce uncertainties related to the crop calendars, an initial model run is performed to select optimal calendars, based on planting and harvesting dates available in the dataset published in Sacks et al. (2010). This dataset includes time windows for the planting and harvesting season for different areas around the country. We ran the model for non-irrigated conditions with minimized nutrient stress, for three different calendar options - early, mid and late planting and harvesting. The option with higher yields for each crop and simulation unit was chosen. We calculated the potential heat units (PHU) for each crop, simulation unit, and planting and harvesting window.

We initialized the model by carrying out spin-up model runs for the period 1980-1990 to equilibrate the nutrient pools in soil, comprising soil organic carbon and total and organic nitrogen and phosphorous. The spin-up runs generated soil profile values that were used as inputs to the final transient model runs. Appendix A provides further detail on the methodology for PHU calculation, model initialization, and spin-up model runs (Table A.2 to Table A.4).

2.2.4 *Crop management scenarios*

We simulated six different crop management scenarios depicting different combinations of fertilizer application and irrigation (see Table 2.1). The first scenario, called "subsistence", assumes crop management with no additional water or fertilizer input. On the other side of the spectrum, two scenarios called "high input" are designed to provide enough fertilizer input to minimize nutrient stress. Other two fertilizer scenarios were designed based on historical fertilizer application data, called "low input" and "mid input", and are intended to mimic the input level of farms with intermediate cropping intensity. The mid and high input scenarios were simulated both for irrigated and non-irrigated conditions, while the subsistence and low input scenarios were simulated only for rainfed conditions.

In the irrigation scenarios, the model supplies irrigation water on each day in which the water stress factor exceeds 20% (water stress trigger of 0.8), thus reducing while still allowing a small degree of water stress. For nitrogen application, the model was set to provide nitrogen when nitrogen stress is above 20% (nitrogen stress trigger of 0.8), with a pre-determined application rate specific to each scenario. When it comes to phosphorus, the model was set to apply a certain application rate before planting. The fertilizer levels and stress triggers used to set up each scenario are better detailed in Table A.2 and Table A.3.

We can assume that the yields estimated in the high-input irrigated and rainfed scenarios correspond, respectively, to the water-limited potential and potential yields for the analyzed crops. Therefore, the difference between the reported yields and the potential yields corresponds in our assumptions to the yield gap.

Table 2.1: Model setup for scenario runs.

Scenario	Fertilizer Application	Irrigation
Subsistence (S)	Off	Off
Low-Input (L)	Low	Off
Mid-Input Rainfed (M1)	Medium	Off
Mid-Input Irrigated (M2)	Medium	Unlimited
High-Input Rainfed (P1)	Unlimited	Off
High-Input Irrigated (P2)	Unlimited	Unlimited

2.2.5 *Water use and efficiency indicators*

The model output of EPIC comprises detailed information on crop growth, water, nutrient, and carbon fluxes in daily, monthly and yearly steps. For this study, we focus on the estimated annual yield (Yd, ton/ha), the growing season evapotranspiration (GSET, mm), and the amount of water provided by irrigation annually (IR, mm).

We chose to use the Hargreaves method in the EPIC Model for estimating evapotranspiration (Hargreaves and Samani, 1985). The blue water corresponds to the IR parameter, and the green water corresponds to the total growing season evapotranspiration (GSET), minus the water application through irrigation.

$$GreenWater(mm) = GSET(mm) - IR(mm) \tag{2.1}$$

The consumptive water use (CWU, m^3/yr), crop water productivity (WP, kg/m^3) and virtual water content (VWC, m^3/kg) in a certain area are defined and calculated as follows.

$$CWU(m^3/yr) = 10 * \sum GSET(mm/yr) * Area_{SimU}(ha) \tag{2.2}$$

$$WP(kg/m^3) = 100 * \frac{Yd(ton/ha)}{GSET(mm)} \tag{2.3}$$

$$VWC(m^3/kg) = 10 * \frac{GSET(mm)}{Yd(ton/ha)} \tag{2.4}$$

Where Yd refers to the crop yield, given in tons per hectare, and $Area_SimU$ corresponds to the area of the simulation unit. We aggregated the yields and water productivities from the simulation unit to the municipal level, by calculating the weighted averages using the simulation unit area divided by the total simulation unit area in each municipality as weights. We then aggregated them to the regional level, using the harvested area per municipality divided by the total harvested area per region as weights.

To estimate the consumptive water use and water productivity for the historical scenario, we used the simulated growing season evapotranspiration from the high-input rainfed scenario aggregated at the municipal level, and the reported yields between 1990 and 2013 (IBGE (Brazilian Institute of Geography and Statistics), 2018). Therefore, we assume that the water use for production in this period comprises only rainfed agriculture, and account only for green water use.

We calculated the potential for implementation of irrigation infrastructure (IP) using two different approaches. First, the potential for irrigation is described as the rate of yield increase between the irrigated and rainfed high-input scenario (IP1), as an indicator of the potential of supplemental irrigation to increase local crop productivity.

$$IP1(\%) = 100 * \frac{Yd_{HI,IRR}(ton/ha) - Yd_{HI,RF}(ton/ha)}{Yd_{HI,RF}(ton/ha)} \tag{2.5}$$

In a second approach, we assume that the more of blue water is necessary to meet the crop water requirements, the higher the likelihood that farmers will make the choice to implement irrigation systems (IP2). It is common to assume that irrigation systems will be implemented if the rate between blue and total water use is above a certain threshold, usually around 10% (Dell'Angelo, Rulli, and D'Odorico, 2018; Rosa et al., 2018). Accordingly, we further estimate the potential for implementation of irrigation (IP2) as the rate between blue and total consumptive water use during the cropping season.

$$IP2(\%) = \sum GSET_{HI,IRR}(mm) \tag{2.6}$$

We estimated the water and land saving potential of each scenario as the difference between the water and land required with the simulated water productivity and yield for each scenario, and the actual water and land requirements to produce the reported crop production ($P_{Reported}$, kg/year) between 1990 and 2013. We calculated the necessary area and consumptive water use for each municipality and aggregated it to the national level.

$$CWU_{Scenario}(m^3/yr) = \sum \frac{P_{Reported}(kg/yr)}{WP_{Scenario}(kg/m^3)} \tag{2.7}$$

$$HA_{Scenario}(ha/yr) = \sum \frac{P_{Reported}(kg/yr)}{Yd_{Scenario}(kg/ha)} \tag{2.8}$$

$$Savings_{Scenario}(\%) = 100 * \frac{HA_{Scenario} - HA_{Reported}}{HA_{Reported}} \tag{2.9}$$

$$= 100 * \frac{CWU_{Scenario} - CWU_{Reported}}{CWU_{Reported}} \tag{2.10}$$

Where P refers to the crop production in the referred geographical unit, in kilograms per year, and HA refers to the harvested area for this specific crop, in the referred geographical unit.

2.2.6 *Data*

Soil parameters of soil depth, percent sand, silt and clay, bulk density, pH, and organic carbon content are obtained from the SoilGrids (Hengl et al., 2014). Soil parameters are available for five soil layers (0-5, 5-15, 15-30, 30-60, 60-100 cm), with a resolution of 1 km. The soil hydraulic properties, of saturated water content and saturated water conductivity, were obtained from the HiHydroSoil Soil Map of Hydraulic Properties (Boer, 2015), with a resolution of 1 km.

The topography maps for the area were obtained from the NASA Shuttle Radar Topographic Mission (SRTM) 90m Digital Elevation Database (v4.1), available through the Consortium for Spatial Information (CGIAR-CSI) of the Consultative Group for International Agricultural Research (CGIAR) (Jarvis et al., 2008). The CGIAR-CSI SRTM Digital Elevation Models have a resolution of 90m at the equator.

Daily climate data on maximum and minimum temperature, precipitation, wind speed, relative humidity, and solar radiation between 1980 and 2013 for Brazil were obtained from the database of daily gridded meteorological variables for Brazil (Xavier, King, and Scanlon, 2016), with a spatial resolution of 15 arcminutes.

The mapping of cropland and harvested areas were obtained from two data sources. The area delimited for cropland in general was based on the European Space Agency's

Climate Change Initiative Land Cover Maps (ESA-CCI LC maps) at the resolution of 1 km (ESA, 2017). The harvested area and crop production per Brazilian municipality were obtained from the Brazilian Statistics Bureau (IBGE (Brazilian Institute of Geography and Statistics), 2018) for around 5500 municipalities and all crops of interest, between 1990 and 2015. The crop calendars were based on the publicly available data set of global planting date patterns developed by Sacks et al. (2010).

We overlaid the datasets with classes of soil texture, cropland area, slope, and altitude at the 1 km resolution to delimitate the simulation units, which became the spatial unit on which the model is run. The crop calendars and weather data were used to calculate the potential heat units necessary for the model setup. The datasets of soil, altitude, crop calendar, and weather were averaged by simulation unit area in order to produce the input files for the model.

2.3 RESULTS

2.3.1 *Yields and water productivity*

The following section describes our results for water footprints, consumptive water use, and water productivities. A detailed comparison of these results with previous studies and with reported data are to be found in Appendix A (Table A.6 - Table A.11).

As expected, higher nutrient and water availability resulted in consistently higher simulated crop yields (Table 2.2). Higher yields related to nutrient application are connected to higher water productivity values, as more output per area also results in more crop per drop. However, we observed that the average water productivity of irrigation scenarios is lower than the water productivity of equivalent rainfed scenarios. This indicates that the increase in water input does not necessarily result in equivalent increases in productivity, resulting in higher amount of water per unit of output.

Table 2.2: Average yields (ton/ha, above) and maximum and minimum regional averages productivity (kg/m^3, below) estimated in this study, for every crop and scenario.

Average yields (ton/ha), national					
Scenario	Cotton	Maize	Second Season maize	Soybean	Wheat
S	1.2	1.2	1.0	1.0	0.6
L	1.9	2.2	1.9	1.9	1.4
M1	3.9	4.7	4.5	3.4	2.7
M2	4.1	4.9	4.8	3.7	2.8
P1	5.1	5.5	5.1	3.6	2.8
P2	5.9	5.8	5.8	3.9	2.9
Water productivity (kg/m^3), regional					
S	0.09-0.17	0.2-0.49	0.18-0.55	0.15-0.37	0.18-0.29
L	0.16-0.24	0.38-0.87	0.49-0.79	0.34-0.6	0.39-0.62
M1	0.33-0.53	0.9-1.61	1.34-1.54	0.66-0.74	0.85-1.11
M2	0.32-0.42	0.88-1.34	1.3-1.53	0.66-0.74	0.82-1.13
P1	0.47-0.64	1.12-1.63	1.38-1.71	0.70-0.75	0.85-1.11
P2	0.46-0.62	1.11-1.37	1.39-1.85	0.47-0.63	0.85-1.13

In order to assess opportunities for changes in yields and water productivity by achieving the potential irrigated and non-irrigated yields, we estimated the water productivities related to measured yields in Brazil in the period 1990-2013. For this, we used an average of the modelled growing season evapotranspiration, i.e. water footprint, for rainfed scenarios. Table 2.3 shows the spatial and temporal average of the growing season evapotranspiration for all crops, for irrigated and rainfed scenarios. The water footprint of the rainfed scenarios consists of only green water, while the irrigated scenario footprints refer to the sum of the green and blue water.

Table 2.3: Average growing season green water use (mm/yr) for irrigated and non-irrigated scenarios, for every crop.

	Cotton	Maize	Maize second season	Soybeans	Wheat
Rainfed Scenarios	607	425	323	501	285
Irrigated Scenarios	713	467	349	551	300

When the crop's water demands are met by supplementary irrigation, the yield increases are much less pronounced than when meeting the crop nutrient demands (Figure 2.2). The effect of supplemental irrigation on yields are mostly negligible for maize and wheat. However, when analyzing the same data regionally, we can observe a more pronounced effect in the south and southeast regions for soybeans and in the northeast region for cotton (see Figure A.4 and Figure A.5). On the other hand, we find that second season maize shows a great increase in yields between the water-stressed and potential yields across the territory, which indicates that water availability could be one of the main limitations for double-cropping expansion (see Figure 2.2 and Figure A.3).

Even though the average water productivities are smaller for irrigated scenarios when compared to the corresponding rainfed scenario with the same level of fertilization, in some cases this goes hand in hand with particularly high increases in yields (e.g. cotton, Figure A.1). When considering regional patterns (Figure A.1 to Figure A.5), we can see that most of the yield increase observed for cotton is concentrated in the Northeast region. The Northeast region is also where the steepest decreases in water productivities are seen for both main and second season maize.

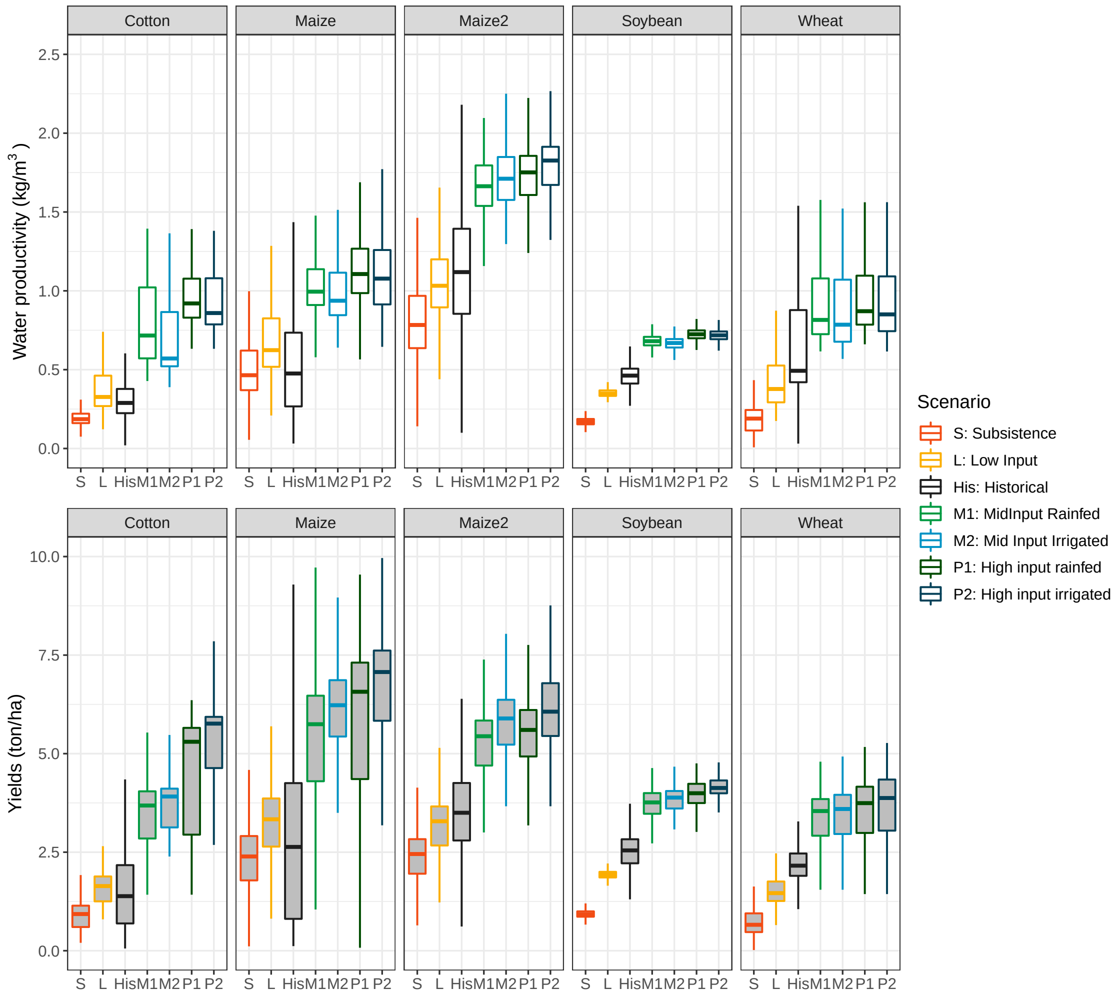


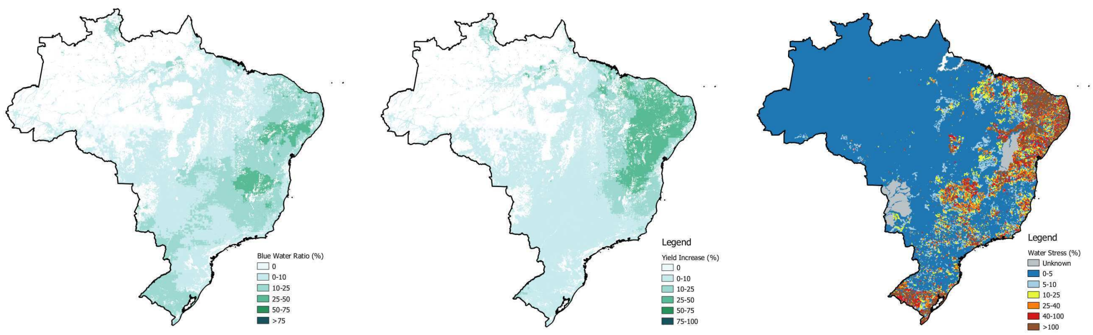
Figure 2.2: Water productivity (above, kg/m^3) and yields (below, ton/ha) statistics per municipality, related to historical data and management scenarios, for all crops.

The full range of scenario results adequately represented the variability of the reported yields observed during the study period for most crops. This is evident when comparing crops that present moderate spatial variability such as wheat and cotton, or presents reported and simulated homogeneous yield values, such as soybeans. On the other hand, the model does not represent well the great spatial variability found in the reported values for maize (Figure 2.2). Maize production is dispersed across the country in a much larger number of municipalities, in both smallholder and commercial farming, and in turn shows a wider reported variability.

2.3.2 *Feasibility of supplemental irrigation*

The results from the scenario analysis indicate that fertilization plays a more dominant role in influencing overall yields than irrigation. However, the balance between the benefits of supplemental irrigation and its influence on annual water use largely depends on the crop, and on local conditions. In this section we analyze which crops and areas of the country could benefit more from additional blue water, as well as where blue water would make up a larger share of total water demand.

Figure 2.3 shows the spatial patterns of differences between high-input non-irrigated and high-input irrigated scenarios. The ratio between blue and total water use demonstrates the share of irrigation in supplying the necessary water for optimal plant growth Figure 2.3a, while the potential changes in yields (Figure 2.3b) demonstrates the regions that would benefit the most from supplemental irrigation, in terms of yield improvements. To illustrate the potential pressure of irrigation on blue water resources, we included in Figure 2.3c the Brazilian Water Agency map with the blue water stress ratio (total water demand, divided by total water availability) per micro-basin (ANA, 2013).



(a) Ratio between blue and total water use (b) Average yield increase in irrigation scenario (c) Blue water stress

Figure 2.3: Ratio between blue and total water use in the irrigation scenarios, averaged for all crops (%) (a); Average yield increase from water-stressed to irrigation scenario, averaged for all crops (%) (b); and blue water stress, defined as the total water use in a basin divided by the total water availability (%), adapted from ANA (2013) (c).

The area where both most blue water use and yield increase because of irrigation happens is the northeast area of the country, an area known for high levels of water stress due to its semi-arid climate. While the share of blue water in total water use is also high in areas in the south of the country, the higher water use does not translate to higher yields for the crops analyzed in this study. These two areas - northeast and outmost south - are also areas known for high levels of water stress resulting from low local water availability (Figure 2.3c).

The areas with high blue water ratio in Figure 2.3a, but low yield increase in Figure 2.3b, are the areas in which there is a sizable increase of consumptive water use by the addition of irrigation, but without a corresponding increase in productivity. These are the areas where most of the reduction of water productivity from one scenario to the other happens. The areas that could benefit the most from irrigation are those with high yield increase (Figure 2.3b), but low rates of blue water (Figure 2.3b).

2.3.3 *Water and land use under management scenarios*

During the period between 1990 and 2013, the production of the four selected crops grew from 46 thousand to 171 thousand tons per year. In the same period, the corresponding harvested area grew from 26 to 46 million hectares (IBGE (Brazilian Institute of Geography and Statistics), 2018). Assuming rainfed conditions for all crops, we estimated the water use in the period 1990-2013 for all crops, as shown in Figure 2.4. As the share of harvested area for main and second season is not known, the total measured harvested area for maize was multiplied by the consumptive water use estimated for both cropping seasons. Therefore, the actual water use for maize in the period 1990-2013, which is a combination of the water use for the two planting modes, is a combination of the two estimates presented in Figure 2.4.

Soybeans use the highest amount of water because of greatest production, which has been expanding across the Brazilian territory steadily in the last decades. Lathuillière et al. (2014) estimated that the total green water use for soybean production in the state of Mato Grosso (the state with the highest soybean production in Brazil) in 2004 was in 28 km^3, while we estimate here a close value of 30 km^3 in the same year, reaching 45 km^3 in 2013.

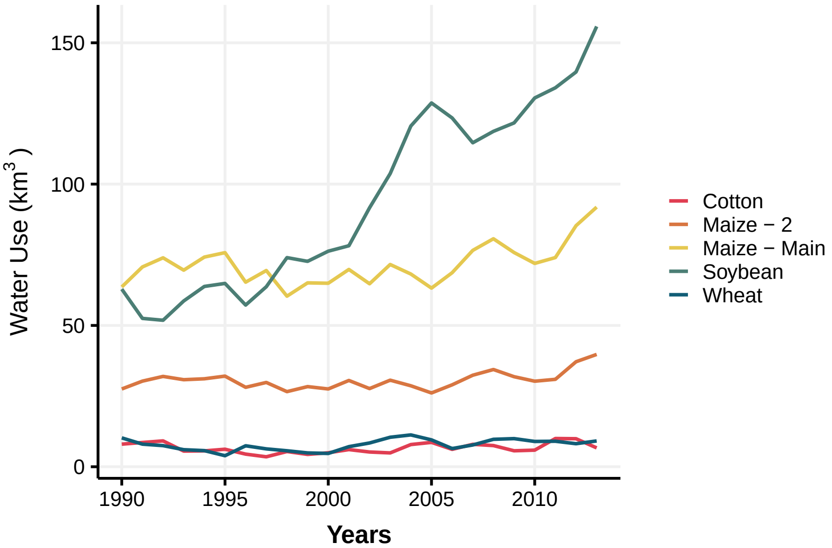


Figure 2.4: Total consumptive water use per crop in the period 1990-2013 (km^3), considering historical harvested area per municipality and estimated rainfed water footprint.

We estimated the amount of resources necessary to obtain the same crop output during this period, under the conditions simulated in the rainfed and irrigated high-input scenarios. The land and water savings are defined as the percentage difference between the scenario-derived and the actual cropland area and water use. As seen in Table 2.4, the average percentage of land savings are higher for all crops. However, the water savings are not necessarily higher in the irrigated scenario.

Table 2.4: Prospective average land and water savings (%) for production of selected crops for 1990-2013, for rainfed and irrigated potential scenarios.

	High-input rainfed	High-input irrigated
Land savings (%)		
Cotton	52	58
Maize – main season	34	49
Maize – 2^{nd} season	38	42
Soybean	36	40
Wheat	45	47
Water savings (%)		
Cotton	52	50
Maize – main season	29	41
Maize – 2^{nd} season	38	40
Soybean	37	36
Wheat	46	44

We analyzed the cropland and total water use required to produce the historical output in Brazil for 1990-2013 for the crops simulated in this study. As seen in Figure 2.5, the gap between the actual and potential land and water use has decreased through the years, as improved agricultural management and higher crop productivity becomes widespread in the country.

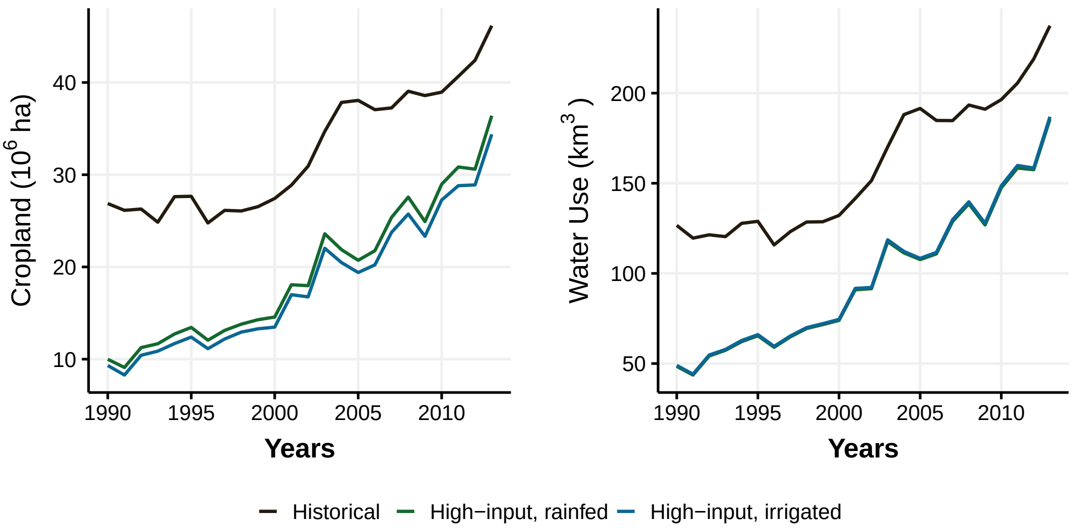


Figure 2.5: Annual cropland area ($10^6 ha$) and consumptive water use (km^3) required for production of reported production between 1990-2013, as well as for the high-input rainfed and irrigated scenarios.

As seen in Table 2.4, the effect of each scenario on water savings is highly dependent on the crop. When adding up all crops, the high-input rainfed and irrigated scenarios ultimately result in a very similar level of water requirements, even though the land requirements are a bit larger for the rainfed scenario.

2.4 DISCUSSION

Our analysis shows a picture of the trade-offs and synergies for land and water use efficiency, looking into different scenarios of irrigation and fertilization. When it comes to changes in overall water use, we see that cropland expansion was the main cause for the general increase of green water use in Brazil, mostly for production of soybeans (see Figure 2.4). The scenario analysis showed that agricultural intensification has the potential to enable the production of the same amount of output on a smaller area and with lower water requirements. The main result of our study is the observed dominance and importance of green water as a resource for agriculture in Brazil. While cropland expansion can be seen as the additional appropriation of green water, intensification can be seen as a strategy for better use of the green water available.

From the results, it can be seen that the implementation of supplemental irrigation did not always result in comparable increases in productivity. The areas in which our model showed that the benefits and relative importance of irrigation would be more pronounced, are also areas known for semi-arid conditions with high-levels of blue water stress. These are also the regions where most of the current irrigation infrastructure exists (ANA, 2017).

We have shown that, in the case of water resources, intensification is a pathway for improving the efficiency of water use, with the consequence of sparing water use in either water-stressed, or water and biodiversity rich areas. When it comes to greenhouse gas emissions, Burney, Davis, and Lobell (2010) showed that land sparing due to agricultural intensification outweighs the emissions related to intensification strategies. It is important to highlight, however, that the focus here is to understand trade-offs related to land and water use, and therefore discount other possible environmental impacts that might result from agricultural intensification, such as greenhouse gas emissions and water quality.

We were able to replicate the range of historical yields and observed water productivities with our setup of the EPIC model. Our results show that we have sufficient plasticity in our results to reconstruct a business-as-usual trajectory of yields. We have also demonstrated (see Appendix A) that the estimated values for water productivity fall within the range of previously reported values, (Lathuillière, 2011; Liu and Yang, 2010; Mekonnen and Hoekstra, 2011); and the same can be said for yields (IBGE (Brazilian Institute of Geography and Statistics), 2018; Mueller et al., 2012). In the absence of spatially explicit crop-specific data on fertilizer and irrigation water use, we opted to explore a full range of possible management options.

Despite the positive evaluation of the model, several shortcomings remain in our modeling approach. Although intercropping is a common practice, our model setup reflected only single cropping. The inclusion of second season maize as a monocrop is a step towards modeling real double cropping systems, yet very simplistic. This approach can reveal certain aspects of the water consumption out of main season, as we have witnessed in the results. The modeling of double cropping is not the focus of this study, yet, it is definitely a very important aspect to be considered in future water consumption related studies.

The choice farmers make in the planting and harvesting dates, as well as the choice of which crops will be grown, depends on a series of factors that include weather, international market prices, and subsidies. We assumed here that crop calendars vary in space, but are static from year to year and are the same for all crop intensification scenarios. The implementation of supplemental irrigation could potentially change the harvesting season or enable for double cropping in certain areas. We did not consider these implications here and only focus on how productivity could change within the current average growing season.

One of the main factors that have allowed the expansion of crop cultivation to different parts of the territory, and the improvement of land productivity is the development of a variety of cultivars adapted to different environments, as well as introduction of new pest control mechanisms. Another possible limitation of our modeling approach is that our model operates only with average and conservative cultivar parameters, which are homogeneous for the study area.

2.5 conclusions

With our modeling framework, we were able to replicate the range of historical yields and observed water productivities of cotton, maize, soybean, and wheat in Brazil. Green water was identified as the main water resource for the crop production. The results also show that the yield increase related to nutrient stress reduction have the highest potential to improve green water productivity.

There is potential for irrigation of these crops in Brazil, with yield improvement resulting from supplemental irrigation. Yet, the highest potential for irrigation mostly overlaps with areas with high levels of blue water stress. The supplemental irrigation would result, in several cases, in reduction of the overall water productivity when compared to rain-fed scenarios. On the other side, fertilizer-related intensification is shown to result in steep improvements in green water productivity. Closing the yield gap through optimal fertilization and irrigation have the potential in Brazil to reduce the demand for land and water, in order of 34-58% of cropland area and 29-52% of total water requirement for the selected crop production.

In consideration of the overuse of blue water worldwide, water-rich countries like Brazil act like vast reserves of green water that are available through global trade of agricultural products. Understanding the role Brazil plays in contributing to global water use, as well as the potential for water savings, was one of the motivations of this study. That is particularly important considering the extent of the recent horizontal expansion of Brazilian agriculture, which resulted in larger land and water resources use, as well as displacement of natural ecosystems. This is one of the very first studies, which analyze the land and water use interactions in Brazilian agriculture at national scale.

BIBLIOGRAPHY

ANA (2013). *Conjuntura dos Recursos Hídricos no Brasil 2013*. Tech. rep. Brasilia: Agencia Nacional das Águas, p. 432. URL: http://conjuntura.ana.gov.br/docs/conj2014{_}inf.pdf.

– (2017). *Atlas Irrigação: uso da água na agricultura irrigada*. Tech. rep. Brasília: Agência Nacional de Águas, p. 86. URL: http://arquivos.ana.gov.br/imprensa/publicacoes/AtlasIrrigacao-UsodaAguanaAgriculturaIrrigada.pdf.

Albuquerque, Monik Fernandes de (2013). "Medições e Modelagem da Pegada Hídrica da Cana-de-Açucar Cultivada no Brasil." Master Thesis. Universidade Federal de Campina Grande, p. 40. URL: http://www.scielo.br/pdf/rbeaa/v19n6/1415-4366-rbeaa-19-06-0521.pdf.

Balkovič, Juraj, Rastislav Skalský, Christian Folberth, Nikolay Khabarov, Erwin Schmid, Mikuláš Madaras, Michael Obersteiner, and Marijn van der Velde (2018). "Impacts and Uncertainties of +2°C of Climate Change and Soil Degradation on European Crop Calorie Supply." In: *Earth's Future* 6.3, pp. 373–395. ISSN: 23284277. DOI: 10.1002/2017EF000629.

Balkovič, Juraj, Marijn van der Velde, Rastislav Skalský, Wei Xiong, Christian Folberth, Nikolay Khabarov, Alexey Smirnov, Nathaniel D. Mueller, and Michael Obersteiner (2014). "Global wheat production potentials and management flexibility under the representative concentration pathways." In: *Global and Planetary Change* 122, pp. 107–121. ISSN: 09218181. DOI: 10.1016/j.gloplacha.2014.08.010.

Boer, Froukje De (2015). *HiHydroSoil: A high resolution soil map of hydraulic properties*. Tech. rep. January. Wageningen, The Netherlands: FutureWater, pp. 1–32. URL: http://www.futurewater.nl/wp-content/uploads/2015/05/HiHydroSoil-A-high-resolution-soil-map-of-hydraulic-properties.pdf.

Bondeau, Alberte et al. (2007). "Modelling the role of agriculture for the 20th century global terrestrial carbon balance." In: *Global Change Biology* 13.3, pp. 679–706. ISSN: 1354-1013. DOI: 10.1111/j.1365-2486.2006.01305.x.

Burney, Jennifer A, Steven J Davis, and David B Lobell (2010). "Greenhouse gas mitigation by agricultural intensification." In: *Proceedings of the National Academy of Sciences* 107.26, pp. 12052–12057. ISSN: 0027-8424. DOI: 10.1073/pnas.0914216107.

Carvalho, André Luiz de and Rômulo Simões Cezar Menezes (2014). "Pegadas hídricas em sistemas agropecuários na região semiárida do Nordeste do Brasil." In: *Revista AgroAmbiente Online* 8.1, pp. 142–148.

Chapagain, Ashok K, a. Y. Hoekstra, and H. H. G. Savenije (2006). "Water saving through international trade of agricultural products." In: *Hydrology and Earth System Sciences* 10.3, pp. 455–468. ISSN: 1607-7938. DOI: 10.5194/hess-10-455-2006.

Davis, Kyle Frankel, Maria Cristina Rulli, Francesco Garrassino, Davide Chiarelli, Antonio Seveso, and Paolo D'Odorico (2017a). "Water limits to closing yield gaps." In: *Advances in Water Resources* 99, pp. 67–75. ISSN: 03091708. DOI: 10.1016/j.advwatres.2016.11.015.

Dell'Angelo, Jampel, Maria Cristina Rulli, and Paolo D'Odorico (2018). "The Global Water Grabbing Syndrome." In: *Ecological Economics* 143, pp. 276–285. ISSN: 09218009. DOI: 10.1016/j.ecolecon.2017.06.033.

Dias, Lívia C.P., Fernando M. Pimenta, Ana B. Santos, Marcos H. Costa, and Richard J. Ladle (2016). "Patterns of land use, extensification, and intensification of Brazilian agriculture." In: *Global change biology* 22.8, pp. 2887–2903. ISSN: 13652486. DOI: 10.1111/gcb.13314.

ESA (2017). *ESA: Land Cover CCI Product User Guide Version 2.0*. Tech. rep. URL: https://www.esa-landcover-cci.org/?q=node/163.

Fader, Marianela, D Gerten, M Thammer, J Heinke, W Lucht, and W Cramer (2011). "Internal and external green-blue agricultural water footprints of nations , and related water and land savings through trade." In: *Hydrology and Earth System Sciences* 15, pp. 1641–1660. DOI: 10.5194/hess-15-1641-2011.

Fader, Marianela, Stefanie Rost, Christoph Müller, Alberte Bondeau, and Dieter Gerten (2010). "Virtual water content of temperate cereals and maize: Present and potential future patterns." In: *Journal of Hydrology* 384.3-4, pp. 218–231. ISSN: 00221694. DOI: 10.1016/j.jhydrol.2009.12.011.

Falkenmark, M. and J. Rockstrom (2006). "The New Blue and Green Water Paradigm : Breaking New Ground for Water Resources Planning and Management." In: *Journal of Water Resource Planning Management* 132.June, pp. 129–132.

Falkenmark, Malin and David Molden (2008). "Wake Up to Realities of River Basin Closure." In: *International Journal of Water Resources Development* 24.2, pp. 201–215. DOI: 10.1080/07900620701723570.

Flach, Rafaela, Ylva Ran, Javier Godar, Louise Karlberg, and Clement Suavet (2016). "Towards more spatially explicit assessments of virtual water flows: linking local water use and scarcity to global demand of Brazilian farming commodities." In: *Environmental Research Letters* 11.7, p. 075003. ISSN: 1748-9326. DOI: 10.1088/1748-9326/11/7/075003.

Folberth, Christian, Thomas Gaiser, Karim C. Abbaspour, Rainer Schulin, and Hong Yang (2012). "Regionalization of a large-scale crop growth model for sub-Saharan Africa: Model setup, evaluation, and estimation of maize yields." In: *Agriculture, Ecosystems and Environment* 151, pp. 21–33. ISSN: 01678809. DOI: 10.1016/j.agee.2012.01.026.

Gerten, D., J. Heinke, H. Hoff, H. Biemans, M. Fader, and K. Waha (2011). "Global Water Availability and Requirements for Future Food Production." In: *Journal of Hydrometeorology* 12.5, pp. 885–899. ISSN: 1525-755X. DOI: 10.1175/2011JHM1328.1.

Gibbs, H. K., A. S. Ruesch, F. Achard, M. K. Clayton, P. Holmgren, N. Ramankutty, and J. A. Foley (2010). "Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s." In: *Proceedings of the National Academy of Sciences* 107.38, pp. 16732–16737. ISSN: 0027-8424. DOI: 10.1073/pnas.0910275107.

Hanasaki, Naota et al. (2013). "A global water scarcity assessment under Shared Socio-economic Pathways - Part 2: Water availability and scarcity." In: *Hydrology and Earth System Sciences* 17.7, pp. 2393–2413. ISSN: 10275606. DOI: 10.5194/hess-17-2393-2013.

Hargreaves, George H. and Zohrab A. Samani (1985). "Reference Crop Evapotranspiration from Temperature." In: *Applied Engineering in Agriculture* 1.2, pp. 96–99. ISSN: 1943-7838. DOI: 10.13031/2013.26773.

Hengl, Tomislav et al. (2014). "SoilGrids1km — Global Soil Information Based on Automated Mapping." In: *PLoS ONE* 9.8. Ed. by Ben Bond-Lamberty, e105992. ISSN: 1932-6203. DOI: 10.1371/journal.pone.0105992.

Hoff, H., M. Falkenmark, D. Gerten, L.J. Gordon, L. Karlberg, and J. Rockström (2010). "Greening the global water system." In: *Journal of Hydrology* 384.3-4, pp. 177–186. ISSN: 00221694. DOI: 10.1016/j.jhydrol.2009.06.026.

IBGE (Brazilian Institute of Geography and Statistics) (2018). *Levantamento Sistemático da Produção Agrícola*. URL: https://sidra.ibge.gov.br/tabela/6588 (visited on 12/13/2018).

Jarvis, A., H.I. Reuter, A. Nelson, and E. Guevara (2008). *Hole-filled SRTM for the globe Version 4, available from the CGIAR-CSI SRTM 90m Database.* Tech. rep. CGIAR. URL: http://srtm.csi.cgiar.org.

Konar, Megan, Jeffrey J Reimer, Zekarias Hussein, and Naota Hanasaki (2016). "The water footprint of staple crop trade under climate and policy scenarios." In: *Environmental Research Letters* 11.3, p. 035006. ISSN: 1748-9326. DOI: 10.1088/1748-9326/11/3/035006.

Lathuillière, Michael J, Mark S Johnson, Gillian L Galford, and Eduardo G Couto (2014). "Environmental footprints show China and Europe's evolving resource appropriation for soybean production in Mato Grosso, Brazil." In: *Environmental Research Letters* 9.7, p. 074001. ISSN: 1748-9326. DOI: 10.1088/1748-9326/9/7/074001.

Lathuillière, Michael Jacques (2011). "Land use effects on green water fluxes in Mato Grosso, Brazil." Master of Science. University of British Columbia.

Lathuillière, Michael, Michael Coe, Andrea Castanho, Jordan Graesser, and Mark Johnson (2018b). "Evaluating Water Use for Agricultural Intensification in Southern Amazonia Using the Water Footprint Sustainability Assessment." In: *Water* 10.4, p. 349. ISSN: 2073-4441. DOI: 10.3390/w10040349.

Liu, Junguo, Jimmy R. Williams, Alexander J.B. Zehnder, and Hong Yang (2007). "GEPIC – modelling wheat yield and crop water productivity with high resolution on a global scale." In: *Agricultural Systems* 94.2, pp. 478–493. ISSN: 0308521X. DOI: 10.1016/j.agsy.2006.11.019.

Liu, Junguo and Hong Yang (2010). "Spatially explicit assessment of global consumptive water uses in cropland: Green and blue water." In: *Journal of Hydrology* 384.3-4, pp. 187–197. ISSN: 00221694. DOI: 10.1016/j.jhydrol.2009.11.024.

Liu, Junguo, Alexander J.B. B Zehnder, and Hong Yang (2009). "Global consumptive water use for crop production: The importance of green water and virtual water." In: *Water Resources Research* 45.5, pp. 1–15. ISSN: 00431397. DOI: 10.1029/2007WR006051.

Mekonnen, M. M. and a. Y. Hoekstra (2011). "The green, blue and grey water footprint of crops and derived crop products." In: *Hydrology and Earth System Sciences* 15.5, pp. 1577–1600. ISSN: 1607-7938. DOI: 10.5194/hess-15-1577-2011.

Molden, David, Theib Oweis, Pasquale Steduto, Prem Bindraban, Munir A. Hanjra, and Jacob Kijne (2010). "Improving agricultural water productivity: Between optimism and caution." In: *Agricultural Water Management* 97.4, pp. 528–535. ISSN: 03783774. DOI: 10.1016/j.agwat.2009.03.023.

Mueller, Nathaniel D., James S. Gerber, Matt Johnston, Deepak K. Ray, Navin Ramankutty, and Jonathan A. Foley (2012). "Closing yield gaps through nutrient and water management." In: *Nature* 490.7419, pp. 254–257. ISSN: 00280836. DOI: 10.1038/nature11420. arXiv: NIHMS150003.

Müller, Christoph et al. (2017). "Global gridded crop model evaluation: benchmarking, skills, deficiencies and implications." In: *Geoscientific Model Development* 10.4, pp. 1403–1422. ISSN: 1991-9603. DOI: 10.5194/gmd-10-1403-2017.

Phalan, Ben, Andrew Balmford, Rhys E. Green, and Jörn P.W. Scharlemann (2011). "Minimising the harm to biodiversity of producing more food globally." In: *Food Policy* 36.SUPPL. 1, S62–S71. ISSN: 03069192. DOI: 10.1016/j.foodpol.2010.11.008.

Philip W. Gassman, Jimmy R. Williams, Verel W. Benson, R. Cesar Izaurralde, Larry M. Hauck, C. Allan Jones, Jay D. Atwood, James R. Kiniry, and Joan D. Flowers (2004). "Historical Development and Applications of the EPIC and APEX models." In: *2004, Ottawa, Canada August 1 - 4, 2004*. St. Joseph, MI: American Society of Agricultural and Biological Engineers, p. 31. ISBN: Working Paper 05-WP 397. DOI: 10.13031/2013.17074. URL: https://lib.dr.iastate.edu/card_workingpapers/422/.

Rockström, Johan and Jennie Barron (2007). "Water productivity in rainfed systems: Overview of challenges and analysis of opportunities in water scarcity prone savannahs." In: *Irrigation Science* 25.3, pp. 299–311. ISSN: 03427188. DOI: 10.1007/s00271-007-0062-3.

Rosa, Lorenzo, Maria Cristina Rulli, Kyle Frankel Davis, Davide Danilo Chiarelli, Corrado Passera, and Paolo D'Odorico (2018). "Closing the yield gap while ensuring water sustainability." In: *Environmental Research Letters*. ISSN: 1748-9326. DOI: 10.1088/1748-9326/aadeef.

Rost, S, D Gerten, and U Heyder (2008). "Human alterations of the terrestrial water cycle through land management." In: *Advances in Geosciences* 18, pp. 43–50. ISSN: 00431397. DOI: 10.5194/adgeo-18-43-2008.

Sacks, William J., Delphine Deryng, Jonathan A. Foley, and Navin Ramankutty (2010). "Crop planting dates: An analysis of global patterns." In: *Global Ecology and Biogeography* 19.5, pp. 607–620. ISSN: 1466822X. DOI: 10.1111/j.1466-8238.2010.00551.x.

Siebert, Stefan and Petra Döll (2008). *The Global Crop Water Model (GCWM): Documentation and first results for irrigated crops*. Tech. rep. March. Frankfurt am Main, Germany: Frankfurt am Main University. URL: http://publikationen.stub.uni-frankfurt.de/frontdoor/index/index/docId/81.

Silva, Vicente de Paulo R. da et al. (2016a). "Virtual water and water self-sufficiency in agricultural and livestock products in Brazil." In: *Journal of Environmental Management* 184, pp. 465–472. ISSN: 10958630. DOI: 10.1016/j.jenvman.2016.10.015.

Silva, Vicente de Paulo R. da et al. (2016b). "Water footprint and virtual water trade of brazil." In: *Water (Switzerland)* 8.11. ISSN: 20734441. DOI: 10.3390/w8110517.

Skalský, Rastislav, Zuzana Tarasovičová, Juraj Balkovič, Erwin Schmid, Michael Fuchs, Elena Moltchanova, Georg Kindermann, and Peter Scholtz (2008). *GEO-BENE global database for bio-physical modeling v. 1.0*. Tech. rep. Laxenburg, Austria: International Institute for Applied Systems Analysis (IIASA), p. 58.

Spera, Stephanie A., Gillian L. Galford, Michael T. Coe, Marcia N. Macedo, and John F. Mustard (2016). "Land-use change affects water recycling in Brazil's last agricultural frontier." In: *Global Change Biology* 22.10, pp. 3405–3413. ISSN: 13541013. DOI: 10.1111/gcb.13298.

Vörösmarty, C J and Dork Sahagian (2000). "Anthropogenic Disturbance of the Terrestrial Water Cycle." In: *BioScience* 50.9, pp. 753–765.

Wada, Yoshihide and Marc F P Bierkens (2014). "Sustainability of global water use: past reconstruction and future projections." In: *Environmental Research Letters* 9.10, p. 104003. ISSN: 1748-9326. DOI: 10.1088/1748-9326/9/10/104003.

Williams, J. W., R.C. Izaurralde, and E. M. Steglich (2008). *Agricultural Policy/Environmental eXtender theoretical documentation*. Tech. rep. June. Temple, Texas: Blackland Research and Extension Center, p. 131.

Wisser, Dominik, Steve Frolking, Ellen M Douglas, Balazs M Fekete, Charles J Vörösmarty, and Andreas H. Schumann (2008). "Global irrigation water demand : Variability and uncertainties arising from agricultural and climate data sets." In: *Geophysical Research Letters* 35.L24408, pp. 1–5. DOI: 10.1029/2008GL035296.

Xavier, Alexandre C., Carey W. King, and Bridget R. Scanlon (2016). "Daily gridded meteorological variables in Brazil (1980-2013)." In: *International Journal of Climatology* 36.6, pp. 2644–2659. ISSN: 08998418. DOI: 10.1002/joc.4518. arXiv: 1311.1716.

Zalles, Viviana et al. (2019). "Near doubling of Brazil's intensive row crop area since 2000." In: *Proceedings of the National Academy of Sciences* 116.2, pp. 428–435. ISSN: 0027-8424. DOI: 10.1073/pnas.1810301115.

3

THE EXPANSION AND INTENSIFICATION OF BRAZILIAN SOYBEAN PRODUCTION AND THEIR EFFECTS ON GREEN WATER FOOTPRINTS

After peer-review, the following chapter has been accepted for publication with modifications as:

Rafaela Ariana Flach et al 2020 *Environmental Research Commununications*. in press https://doi.org/10.1088/2515-7620/ab9d04

The processed input and results related to this paper are available as open data as:

Flach, Rafaela. (2020). The effects of cropping intensity and cropland expansion of Brazilian soybean production on green water flows. *Max Planck Society*. https://dx.doi.org/10.17617/3.3x

Rafaela Flach (R.F.) and the other co-authors contributed to the paper as follows: R.F. planned and carried out the model simulations. M.F. supervised the design of this research work and the interpretation of its findings. C.F. and R.S. provided fundamental guidance on the technical aspects of the model, and supervised the result analysis. K.J. supervised the design of the research work, and the revision of the text. R.F. analyzed the data and developed the approach for analysis of the presented results. R.F took the lead in writing the manuscript, while all other co-authors provided critical feedback on the manuscript and helped to finalize this publication.

The expansion and intensification of Brazilian soybean production and their effects on green water footprints

Rafaela Flach[1,2], Marianela Fader[3], Christian Folberth[4], Rastislav Skalský[4,5], Kerstin Jantke[6]

[1] Research Unit Sustainability and Global Change, Universität Hamburg, Hamburg, Germany.
[2] International Max Planck Research School on Earth System Modelling (IMPRS-ESM), Max Planck Institute for Meteorology, Hamburg, Germany.
[3] International Centre for Water Resources and Global Change (UNESCO), Federal Institute of Hydrology, Koblenz, Germany.
[4] International Institute for Applied Systems Analysis, Ecosystem Services and Management Program, Laxenburg, Austria
[5] National Agricultural and Food Centre, Soil Science and Conservation Research Institute, Bratislava, Slovak Republic
[6] Center for Earth System Research and Sustainability, University of Hamburg, Hamburg, Germany.

ABSTRACT

Alongside cropland expansion, agricultural intensification practices modify water consumption and land and water productivity. Particularly, one form of agricultural intensification known as multi-cropping (the cultivation of a piece of land sequentially more than once a year) results in greater agricultural output per unit of land, as well as more productive use of the available water throughout the annual rainfall cycle. We investigate the influence of these two processes – cropland expansion and agricultural intensification – in agricultural green water use in Brazilian agriculture. We applied the biophysical crop model EPIC to estimate yields and green water use for single and double cropping of soybeans and maize in Brazil. The first part of our study analyses changes in soybean water use and virtual water content nationwide between 1990 and 2013, and in a second part we look into the effect of double-cropping on water use for soybeans and maize in the Brazilian states of Paraná and Mato Grosso between 2003 and 2013. The results show that cropland expansion plays a more prominent effect in green water use for production of soybeans than intensification, and harvested area increase was responsible for the appropriation of an additional 95 km^3 of green water in 2013, when compared to 1990. The yield increase in this period, however, contributed to a more productive use of water resources throughout the country. When comparing single and double cropping systems, an even higher improvement of resource use per unit of output is observed. We estimate that an additional green water footprint of around 26 km^3 related to second season maize was appropriated without expansion of cropland in 2013. We observed that not accounting for double-cropping practices when estimating water footprints results in biases, not only in the total amount of water and land used for agriculture, but also regarding the distribution of water use throughout the annual cycle. We discuss the importance of considering multi-cropping practices when assessing green water sustainability, and the limits to green water use.

Keywords: Green Water; Sustainability; EPIC; Crop Modeling; Water Footprint; Cropping intensity; Brazil

3.1 introduction

One of the main limitations for the increase in agricultural production in the future, to meet increasing demands for food, feed and biomass, is the availability of water and land resources, which are also needed as inputs for other economic sectors. Furthermore, cropland expansion has been one of the main drivers of habitat and biodiversity loss worldwide (Foley, 2005; Gibbs et al., 2010).

The limitations for water availability depend highly on location, and whether the water use is based on blue (surface or groundwater available for irrigation) or green (precipitation water available in the soil) water. Global crop production is heavily based on green water, as it is estimated that food production consumes about 4–5 times more green than blue water (Hoff et al., 2010). Increasing limitations to expansion of irrigation, i.e. appropriation of blue water, is evidenced worldwide both by a growing number of river basin "closures" (Falkenmark and Molden, 2008) and overuse of non-renewable groundwater resources (Wada and Bierkens, 2014). As any expansion of agricultural land also increases the appropriation of green water, cropland expansion is instrumental in re-allocating green water towards agriculture, or towards one certain type of agricultural production (Quinteiro et al., 2015; Ridoutt and Pfister, 2010; Schyns et al., 2019). The availability of green water is limited, however, both locally by precipitation regimes, and limits to cropland expansion for protection of ecosystems and their services (Schyns et al., 2019).

The way green water is consumed in agricultural land is not only influenced by cropland expansion, but also by changes in agricultural management and cropping intensity. Agricultural intensification that results in yield increases changes the water productivity of agricultural regions, thus reducing the amount of crop obtained for each drop of green water used (Rockström and Barron, 2007). One of the forms of agricultural intensification is multi-cropping. Even though the multi-cropping concept can refer to a range of agricultural practices, here we will focus on double-cropping, where two crops are harvested sequentially in a calendar year (Borchers et al., 2014). The average number of crops harvested sequentially per year is defined as cropping intensity (Siebert, Portmann, and Döll, 2010). Globally, the regions where crops are usually harvested two or more times per year are situated in highly populated, often irrigated tropical or subtropical lowlands (Siebert, Portmann, and Döll, 2010). The proportion of cropland with double-cropping was 2% in the United States between 1999 and 2012 (Borchers et al., 2014), around 35% in 2005 in India (Biradar and Xiao, 2011), and 34% in 2002 in China (Yan et al., 2014; Zhao et al., 2016).

In Brazil, the development of soybean varieties with more flexible planting dates and cycle length options allowed farmers to plant a second crop after soybeans in the same field (Pires et al., 2016); this second crop, called safrinha, is most of the time maize, and not so commonly cotton or soybeans itself. The harvested area with second-season maize reached around 8 million hectares (IBGE (Brazilian Institute of Geography and Statistics), 2018), and around 58% of Brazilian maize is planted as a second crop in 2015 (Pires et al., 2016). In the state of Mato Grosso, the proportion of the cultivated area harvesting two successive crops increased from 6% to 30% in only six years (Arvor et al., 2012).

Between 2000 and 2010, harvested area grew roughly four times faster than cropland area globally (Ray and Foley, 2013), and global harvest areas could be further expanded by up to 37.5% of current global cropland by closing cropping frequency gaps (Wu et al., 2018). Beyond the effects on agricultural production, multiple cropping practices have different effects on the earth system: satellite data has shown that multiple cropping practices were responsible for a large observed increase in leaf area, mainly in India and China (Chen et al., 2019). Nevertheless, cropping frequency and multiple-cropping practices are commonly not taken into account in most global water footprint assessments (Hanasaki et al., 2010; Liu and Yang, 2010; Mekonnen and Hoekstra, 2011), and when assessing limits to appropriation of green water (Schyns et al., 2019) and its scarcity (Schyns, Hoekstra, and Booij, 2015).

The objective of our study is to estimate and evaluate the influence of expansion and intensification in water use associated to soybean production in Brazil, and to analyse the particular influence of double-cropping in conjunction with maize on water use. For this, we use a crop model to estimate water use of soybean and maize, and analyse the results in terms of the yearly total water use, water use per area, and per ton of product. The first part of the analysis is focused on the effect of expansion and intensification on soybean production in Brazil from 1990 to 2013. In the second part of this article, we present a case study of water use of soybean and maize in single and double-cropping systems in the states of Paraná and Mato Grosso.

Although the soy-cotton and soy-soy combinations are also used, the soybean-maize double-cropping mode as it is by far the most common form of double-cropping in Brazil (Abrahão and Costa, 2018). We chose the states of Paraná and Mato Grosso as these have the highest soybeans production and rates of double cropping. Around 48% of the country's soybeans were produced in these two states, and 65% of their maize production occurred as a second crop in 2013 (IBGE (Brazilian Institute of Geography and Statistics), 2018).

In this study we also shed light on the importance of cropping frequency in the estimation of green water use, and identify the ways in which not considering these management practices biases the accounting of water footprints, as well as the implications these biases could have in the assessment of the sustainability of green water use. We aim to provide insights to the importance of cropland expansion to appropriation of green water resources, as well as the importance of management for the better use of these resources.

3.2 methods

3.2.1 *Data sources*

Table 3.1: Summary of all the data sources used to produce the results presented in this article, and in which phase of the analysis each dataset was used.

Type	Source	Application
Weather	Daily gridded meteorological variables in Brazil (1980–2013) (Xavier, King, and Scanlon, 2016).	Model input
Soil	SoilGrids250: Global gridded soil information based on machine learning (Hengl et al., 2014).	Model input, simulation unit delimitation
Terrain	SRTM 90m Digital Elevation Database v4.1 (Jarvis et al., 2008).	Model input, simulation unit delimitation
Land Use	Patterns of land use, extensification, and intensification of Brazilian agriculture (Dias et al., 2016).	Simulation unit delimitation
Agricultural Production	SIDRA Database (IBGE (Brazilian Institute of Geography and Statistics), 2018).	Simulation unit delimitation, result analysis
Crop Calendars	Planting windows for single- and double-crop soy in Brazil (Abrahão and Costa, 2018). & Data set of global crop planting and harvesting dates (Sacks et al., 2010).	Model input

3.2.2 *Model setup*

3.2.2.1 *General modelling approach*

We use the crop model Environmental Policy Integrated Climate (EPIC) to simulate evapotranspiration in soybean and maize production in Brazil for single and double cropping systems. Albeit the estimation of crop yields is a main purpose of crop models, the accuracy at large scales is often highly limited due to lack of suitable data for calibration, lack of spatially explicit management data, and exogenous factors affecting yields such as pests and diseases, which are typically not represented in crop models. Hence, we opted to use the crop model for estimating crop water requirements while relying on reported production statistics. We classified the Brazilian territory in more than 80 thousand simulation units, and set up the model input based on the assumption that these units are homogeneous in terms of elevation, slope, soil properties and agricultural management.

We set up three different model simulation setups, for (i) single-cropping soybeans, (ii) single-cropping maize, and (iii) soybeans and maize grown in a double-cropping system. The water use was calculated with the use of the estimated growing season evapotranspiration (GSET) of the selected crops. As these results are highly dependent on the start and duration of the cropping season, we analysed the sensitivity of the model results to these two factors. Within the EPIC model it is possible to choose from five different methods for calculating potential evapotranspiration; here we used the Hargreaves method (Hargreaves and Samani, 1985). We also tested the sensitivity of the model results to the chosen evapotranspiration estimation method (see Figure B.6 to Figure B.9).

The crop calendars for soybean and soybean-maize production were obtained from the dataset of planting windows for single- and double-crop soy in Brazil (Abrahão and Costa, 2018), while the calendars for maize production were obtained from the dataset of global crop planting and harvesting dates (Sacks et al., 2010). We set up scenarios of planting and harvesting dates based on these calendars, performed a sensitivity analysis of these calendar scenarios, and selected the calendar options that yielded the highest overall productivity. EPIC uses daily accumulated heat units to regulate crop growth, and requires an estimation of potential heat units (PHUs, ° C) accumulated by a crop from sowing to maturity. We calculated the PHUs based on the planting and harvesting dates, and the available climate data.

Due to the complexity of Brazilian agriculture and Brazil's geographical heterogeneity, simplifications were necessary in our EPIC modelling approach. We did not consider the effect of tillage and pest control, and the cultivar parameters were considered homogeneous for the entire territory. Here we assumed all single and double-cropping production to be rainfed. Although there are areas in Brazil where irrigated production occurs, this is not the case for most of the country's soybean production (ANA, 2017). Furthermore, by modelling rainfed conditions we could also investigate the relationship between production, water use, and precipitation variability in these agricultural production systems.

Section B.2 presents more detailed information on the EPIC model, the data sources used in this study, the methods used to delimitate the simulation units, the crop calendars, the calculation of the potential heat units, and a flowchart explaining all the stops in the model simulation.

3.2.2.2 *Water use indicators*

The model provides the actual growing season evapotranspiration (GSET) for each simulation unit, crop, and cropping cycle. The GSET per municipality was calculated as the area-weighted average of the GSET values in the simulation units within the municipality. The green water use (GWU, also known as water footprint) per year in each municipality is calculated as the multiplication of the GSET by the harvested area in that municipality.

$$GWU_{Mun}(km^3) = 10^{-8} * GSET_{Mun}(mm) * HarvestedArea_{Mun}(ha) \tag{3.1}$$

To aggregate the CWU to the state, regional and national levels, we sum up the crop specific water requirements in m^3 for each municipality within these spatial units. Figure B.1 shows the division of the country in states and regions.

To calculate the virtual water content (VWC) on different spatial units, we divided the GWU in that spatial unit by the total amount of crop produced in that area in that year.

$$VWC(m^3/ton) = 10^9 * CWU(km^3)/Production(ton) \tag{3.2}$$

The average annual crop evapotranspiration (ACET) in a spatial unit corresponds to the total CWU divided by the total harvested area of that crop in that spatial unit.

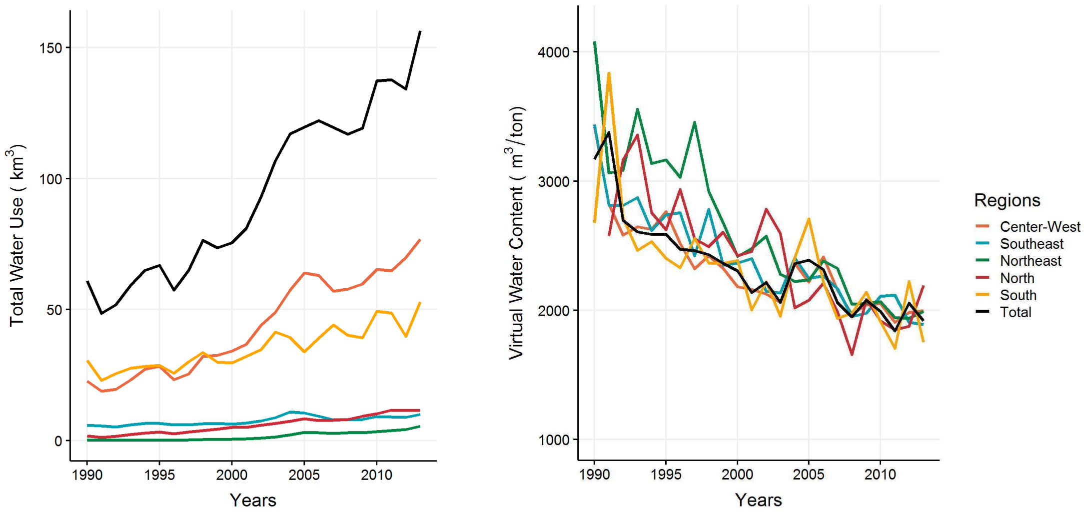
$$ACET(mm) = 10^{-8} * GWU(km^3)/HarvestedArea(ha) \tag{3.3}$$

The data on harvested area and production for each crop and municipality was obtained from the SIDRA Database of the Brazilian Institute for Geography and Statistics (IBGE (Brazilian Institute of Geography and Statistics), 2018). The data on harvested area and production of second season maize is only available after 2003. We assumed here that all harvested area overlap between soybeans and second season maize corresponds to harvested area of double-cropping soybeans, and the remaining is considered single-cropping soybean harvested area.

3.3 RESULTS

3.3.1 *Effects of expansion and intensification on soybean water footprints*

With the use of the yearly GSET estimations, we evaluated the evolution of the water footprints and virtual water content for production of soybeans between 1990 and 2013. In order to analyze solely the effect of expansion and productivity improvements, we assumed all soybeans were grown in single-cropping systems, and analyzed intensification only through the changes in yields. Figure 3.1 shows the changes in green water use in km^3 for all Brazilian macro-regions, as well as the virtual water content of soybeans in m^3/ton, between 1990 and 2013.



(a) Water use (km^3)

(b) Virtual water content (m^3/ton)

Figure 3.1: Time series of total water footprint for production of soybeans (left, km^3) and of virtual water content (right, m^3/ton) between 1990 and 2013.

The overall growth in green water footprints for soybean production happened mostly as a consequence of cropland expansion, accompanied with a steady increase in water productivity. The most dramatic changes have happened in the center-west and south regions of the country, where most of the cropland expansion has happened in the period of analysis. The reduction in virtual water content – and therefore increase in water productivity - was observed consistently across all regions, reaching an average value around 2000 m^3/ton, similar to values previously reported for Brazilian soybeans (Hanasaki et al., 2010; Tuninetti et al., 2017).

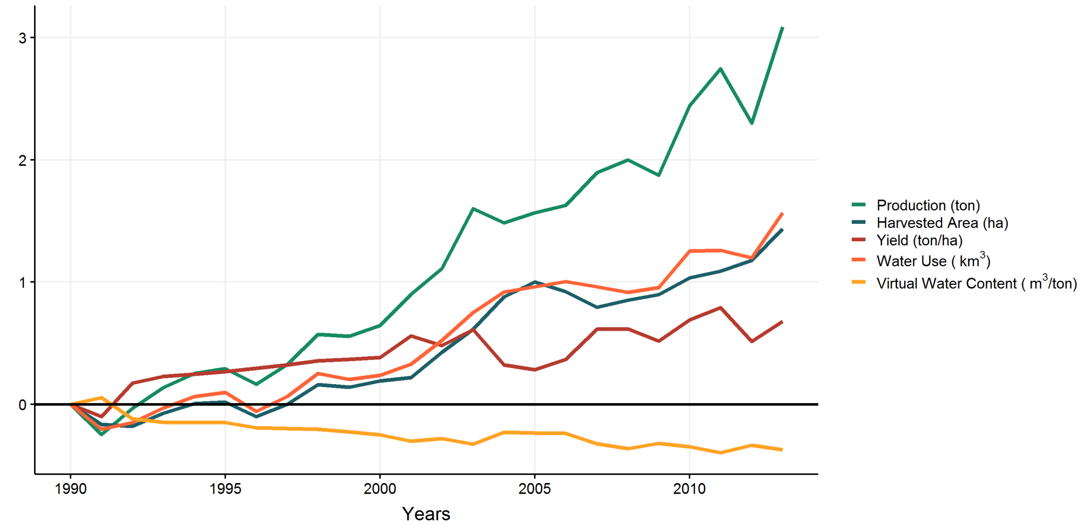


Figure 3.2: Relative change for production, harvested area, water use and virtual water content for soybean production between 1990 and 2013 using 1990 as the baseline.

In order to further illustrate the differentiated influence of expansion and intensification on water use and productivity, Figure 3.2 shows the relative changes in use and use intensity of land and during this period. The increase in land and water productivity result in a de-coupling between the increases in harvested area and water use, and the increase in production. While the output of soybeans grew 308% during this period, the harvested area and water use increased 143 and 156%, respectively. The virtual water content was reduced by 37%.

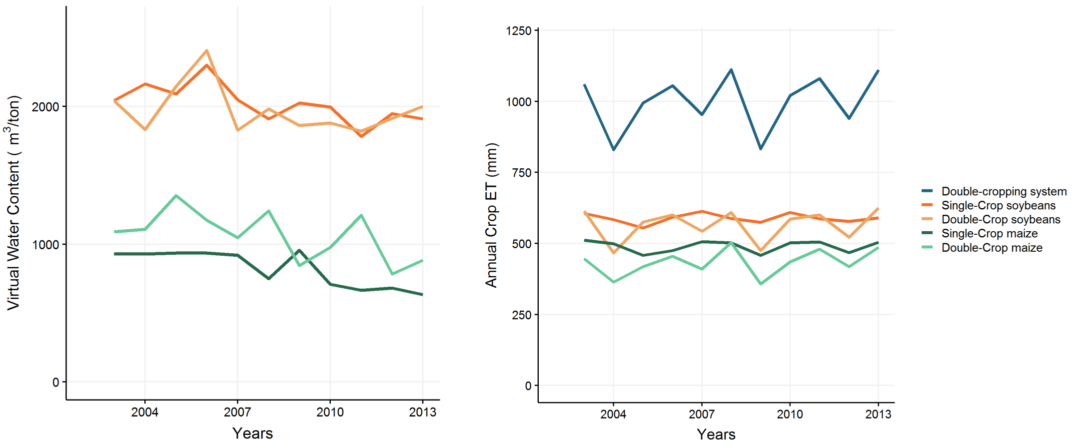
3.3.2 *Water use under single and double cropping systems*

The results presented in the last session are, however, incomplete if we don't consider the existence of double-cropping as a type of agricultural intensification that effects water and land use. Variability in cropping intensity is one of the causes of mismatch between global cropland and harvested area. Here we demonstrate also how cropping intensity can change the accounting of water use and water use intensity in the Brazilian context.

In this section we assess the accounting of water footprints considering the existence of double-cropping systems in the states of Paraná and Mato Grosso between 2003 and 2013. Section 3.3.2.1 demonstrates differences in water use intensity, Section 3.3.2.2 explores the changes in overall water use, and Section 3.3.2.3 shows how the changes in water use are monthly distributed. The results for the entire country can be found in Section B.3.3.

3.3.2.1 *Water use productivity*

Here we evaluate changes in the intensity of water use both in terms of its use of land and in terms of the amount of crop per drop, and how is affected by analyzing the system with consideration of double-cropping. This is done by calculating the virtual water content (m^3 per ton of product) and the annual crop evapotranspiration (Figure 3.3).



(a) Virtual water content (m^3/ton)

(b) Annual crop evapotranspiration (mm)

Figure 3.3: Virtual water content (m^3/ton, left) and annual crop evapotranspiration (mm, right) for single and double-cropping soybeans and maize.

The growing season evapotranspiration for double-cropping crops are in general lower due to a shorter cropping season, and presents higher interannual variability (Figure 3.3b, Figure B.12). The virtual water content, on the other side, is influenced both by the crop evapotranspiration and land productivity. In the states of Mato Grosso and Paraná, the water productivity of soybeans is rather similar for the two cropping practices, as a result of both similar yields and similar water requirements. That is not the case in the national scale, as yields in areas with high rates of double-cropping tend to be higher than the national average (Figure B.13). In the case of maize, the water requirement per ton of single-cropping maize is lower due to the fact that single-cropping maize yields in these states are abnormally high when compared to the yields for dougle-cropping maize, as well as with the national average (Figure B.2).

3.3.2.2 *Evolution of resource use*

The total water footprint for soy and maize is the sum of the water footprints of all the two crops under the two different cropping seasons, as seen in Figure 3.4. The total water footprint of soybeans and maize increased 40 (from 70 to 110) km^3 between 2003 and 2013 in the selected states. Out of this increase in water footprints, 13 km^3 (32%) happened in double-cropping systems. We estimate that, in 2013, 26 km^3 of the joint footprint was dedicated to second season maize. As a consequence, a large share of the additional green water resources appropriated in this period in the two states required no expansion in cropland area in this period.

We also observed that the consideration of cropping intensity did not only influence the relationship between water and land resources, but also influenced the estimation of water footprints for each of these crops. This is a result of the fact that the growing season evapotranspiration for crops in multiple-cropping systems tends to be shorter, in order to fit the rainy season (Figure 3.3b, Figure B.12). The final effect in the water footprint accounting in this case is to result in a smaller value for overall footprint when considering double-cropping. In the context of this study, considering double-cropping systems resulted in values of yearly total water footprint 0.5-20% lower than when estimating considering only single-cropping calendars

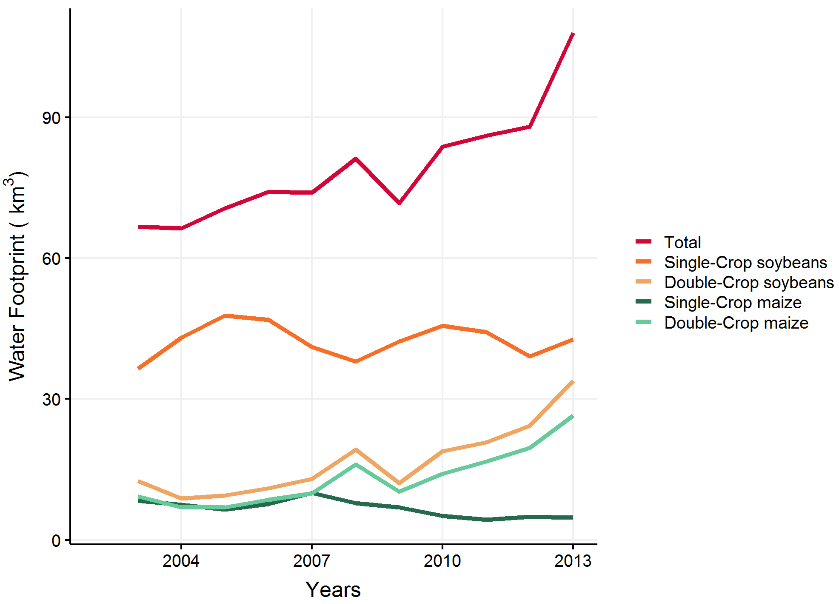


Figure 3.4: Water footprint (km^3) estimates for soybeans and maize in Mato Grosso and Paraná taking into account single- double-cropping conditions.

3.3.2.3 *Annual evapotranspiration cycle*

The overall result of the two processes observed in the previous section is that, even though both the total combined cropland and water footprint are smaller, the water use per area is higher in single cropping systems compared with double cropping systems. These practices disassociate the linear relationship between cropland area and water use, while maintaining the relationship between harvested area and water use. By taking better advantage of the length of the rainy season, double-cropping systems increase the total evapotranspiration across the yearly cycle. In Figure 3.5, we show how the average evapotranspiration annual cycle looks like for the states of Mato Grosso and Paraná, for single and double-cropping systems. It is important to highlight that this represents the evapotranspiration cycle of the two crops during the cropping season, excluding soil evaporation outside of the cropping season, or cover crops.

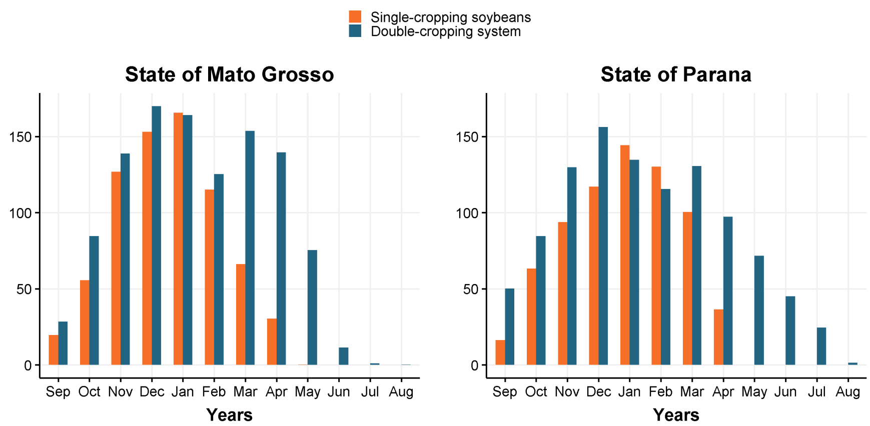


Figure 3.5: Average monthly evapotranspiration (mm) for single and double cropping systems in the State of Mato Grosso.

As a result of the higher use of the water available through precipitation across the year, the double-cropping systems also present a different ratio between the growing season evapotranspiration and the total annual evapotranspiration. We found that the average ratio for single-cropping soybeans and maize are similar and around 0.6, while the ratio for double-cropping systems is in average around 0.9 (as seen in Figure B.15).

3.4 DISCUSSION

3.4.1 *Soybean production: larger water footprints, higher water productivity*

Brazil is a world leader in production and export of agricultural products, and one of the world's main virtual water exporters (Dalin et al., 2012; Silva et al., 2016b). The country's agricultural sector has undergone severe changes in the last decades, at the same time modernizing and expanding its cropland area (Dias et al., 2016; Zalles et al., 2019). Soybean production has been at the forefront of these changes, being responsible not only for a large share of the cropland expansion, but also of the expansion-related deforestation (Gibbs et al., 2015, 2010) and impacts on the water resources (Hunke et al., 2015; Spera et al., 2016).

The results presented here demonstrate that the expansion of soybean production is connected to an increase from 61 to 156 km^3 in water footprints during the same period. The additional appropriation of around 95 km^3 of green water was enabled by the increases in harvested area observed in this period Figure 3.1. Most of this additional resource constitutes green water that became available to the international market, as a large share of this production is intended for the external markets in the European Union and China (Flach et al., 2016; Godar et al., 2015).

Our results demonstrate a decrease in the virtual water content from 3045 to 1913 m^3/ton between 1990 and 2013. This result resembles closely the decrease in virtual water content estimated by Tuninetti et al. (2017) for global soybean production. The soybean virtual water content of 1918 m^3/ton in 2013 is much lower than the previously reported average global values, of 2107 m^3/ton (Mekonnen and Hoekstra, 2011) and 2046 m^3/ton (Siebert and Döll, 2010).

3.4.2 *Cropping frequency and improving agricultural water use assessments*

Explicitly accounting for double-cropping practices results in more realistic assessments of water use, the relationship between water and land use, as well as the limits to availability of water for agriculture. Given the high levels of multi-cropping practices in the tropics (Biradar and Xiao, 2011; Yan et al., 2014; Zhao et al., 2016) and the growth of these practices in other regions of the world (Borchers et al., 2014; Estel et al., 2016), it is important to consider the biases implied in not considering these practices. Here we identified some of the ways in which overlooking multi-cropping practices can generate uncertainty or compromise the relevance of water footprint assessments.

One source of uncertainty is derived from the diversity of planting and harvesting calendars in different cropping practices. As demonstrated in our study, crop water requirement values are very sensitive to the start and length of the cropping season (Section B.3.1), which was also identified by Tuninetti et al. (2015). We found that growing season evapotranspiration values both due to differences in the length or the start of the cropping season, but also due to interannual variability (Figure 3.3). The overall error in estimating the total water footprints for the states of Mato Grosso and Paraná ranged between 0.5 and 20%, depending on the year.

Even though for each crop the evapotranspiration corresponds to the evapotranspiration that happens during its growing season, the yearly crop evapotranspiration in a double-cropping system in a given area is the sum of the growing season evapotranspiration for the two crops. Consequently, the water use per unit of area is significantly higher than any of the other single crops on their own (Figure 3.3). Had we considered the two crops here as planted always independently, the average annual evapotranspiration of the soybeans and maize production across the territory of the two states would total around 560 mm/year. However, by considering the mixture between single-cropping systems, and cropland area different than the total harvested area, the average evapotranspiration would correspond to around 685 mm/year.

Another source of bias is how the relationship between crop evapotranspiration and total evapotranspiration is accounted. When estimating limits to appropriation of water use, Schyns, Hoekstra, and Booij (2015) considered the ratio between the crop evapotranspiration based on values previously reported in the literature – 0,6 (Hanasaki et al., 2010) and 0,8 (Liu and Yang, 2010). We found the values for the single crops to be very similar, of 0,6 for the single crops, but that in the Brazilian double-cropping soy-maize system this value can reach much higher values, approaching an average of 0,9.

3.4.3 *Implications for green water use sustainability*

The results we discussed in the previous sections have implications also for the analysis of green water use sustainability, and how we estimate the limits to green water availability. As green water is accessed through land use change, additional cropland area can be seen as expansion of green water appropriation for a certain activity, either by displacement of natural ecosystems or by displacement of other land use purposes. Expansion of agriculture into areas with high green water availability, and closing the cropping frequency gap are two of the main ways of tapping into unused green water sources (Schyns et al., 2019; Wu et al., 2018). The changes observed in our results show these two very different processes in motion.

Our study provided an assessment of the volumetric water use changes in single and double-cropping systems, but did not further investigate the impacts of the green water use (Lathuillière et al., 2018b). Land use change affects the partitioning of blue and green water and the local moisture recycling capacity, its impacts depend on what type of potential natural vegetation or previous land use was replaced (Quinteiro et al., 2015).

In Brazil, the replacement of natural vegetation by cropland has caused concern, as the lower levels of evapotranspiration threaten the moisture transport across the country (Marengo et al., 2011). Keys, Wang-Erlandsson, and Gordon (2016) identified that the land moisture originating from the Mato Grosso vegetation not only regulates internal precipitation, but also benefits a region downwind that includes the La Plata River basin and the megacities of Sao Paulo and Rio de Janeiro. Spera et al. (2016) found that, in the Brazilian Cerrado region, double-cropping systems behave more akin to the natural vegetation, when it comes to moisture flows from land. In this case, a higher evapotranspiration annual profile can be seen not as an impact, but an ecosystem service (Keys, Wang-Erlandsson, and Gordon, 2016).

Our results show that, in the states of Mato Grosso and Paraná, the annual evapotranspiration profile of the double-cropping system provides a nearly-double amount of moisture to the atmosphere. Further research could provide a deeper understanding on whether this increase in moisture is sustainable, by analysing the type of vegetation replaced (pasture, other crops or natural vegetation), and the moisture fluxes of the natural vegetation (in the case of Paraná the Atlantic Forest, and in the case of Mato Grosso, Amazon and Cerrado biomes).

3.5 conclusions

In this paper we presented an assessment of water use for Brazilian soybean and maize taking into account the role of expansion and intensification processes, with special attention to the effects of double-cropping practices. We verified the influence of area expansion in green water use, observing an increase of 143% and 156% in soybean harvested area and water use, respectively. During the same period, the virtual water content was reduced by 37%, demonstrating the role of yield improvements on a more productive use of water resources throughout the country.

We demonstrate the application of a study case considering the effects of double-cropping practices on water use, annual evapotranspiration and virtual water content. Our results show that several biases can be found when not considering multiple-cropping practices when assessing water footprints, especially regarding the relationship between land and water use. We make a case for further investigation of the importance of cropping frequency on the sustainability and on the limits to green water use. Exploiting the potential for double cropping could be a sustainable option to increase agricultural production without further land conversion, while taking better advantage of the available water throughout the year. However, further investigation is necessary to investigate the locally-specific impacts of these practices on water flows.

BIBLIOGRAPHY

ANA (2017). *Atlas Irrigação: uso da água na agricultura irrigada*. Tech. rep. Brasília: Agência Nacional de Águas, p. 86. URL: http://arquivos.ana.gov.br/imprensa/publicacoes/AtlasIrrigacao-UsodaAguanaAgriculturaIrrigada.pdf.

Abrahão, Gabriel M. and Marcos H. Costa (2018). "Evolution of rain and photoperiod limitations on the soybean growing season in Brazil: The rise (and possible fall) of double-cropping systems." In: *Agricultural and Forest Meteorology* 256-257.March, pp. 32–45. ISSN: 01681923. DOI: 10.1016/j.agrformet.2018.02.031.

Arvor, Damien, Margareth Meirelles, Vincent Dubreuil, Agnès Bégué, and Yosio E. Shimabukuro (2012). "Analyzing the agricultural transition in Mato Grosso, Brazil, using satellite-derived indices." In: *Applied Geography* 32.2, pp. 702–713. ISSN: 01436228. DOI: 10.1016/j.apgeog.2011.08.007.

Biradar, Chandrashekhar M. and Xiangming Xiao (2011). "Quantifying the area and spatial distribution of double- and triple-cropping croplands in India with multi-temporal MODIS imagery in 2005." In: *International Journal of Remote Sensing* 32.2, pp. 367–386. ISSN: 13665901. DOI: 10.1080/01431160903464179.

Borchers, Allison, Elizabeth Truex-powell, Steven Wallander, and Cynthia Nickerson (2014). *Multi-Cropping Practices : Recent Trends in Double Cropping*. Tech. rep. 125. United States Department of Agriculture, Economic Research Service. URL: https://www.ers.usda.gov/webdocs/publications/43862/46871{_}eib125.pdf?v=41787.

Chen, Chi et al. (2019). "China and India lead in greening of the world through land-use management." In: *Nature Sustainability* 2.2, pp. 122–129. ISSN: 2398-9629. DOI: 10.1038/s41893-019-0220-7.

Dalin, Carole, Megan Konar, Naota Hanasaki, and Ignacio Rodriguez-iturbe (2012). "Evolution of the global virtual water trade network." In: *Proceedings of the National Academy of Sciences* 109.21, pp. 8353–8353. ISSN: 0027-8424. DOI: 10.1073/pnas.1206123109.

Dias, Lívia C.P., Fernando M. Pimenta, Ana B. Santos, Marcos H. Costa, and Richard J. Ladle (2016). "Patterns of land use, extensification, and intensification of Brazilian agriculture." In: *Global change biology* 22.8, pp. 2887–2903. ISSN: 13652486. DOI: 10.1111/gcb.13314.

Estel, Stephan, Tobias Kuemmerle, Christian Levers, Matthias Baumann, and Patrick Hostert (2016). "Mapping cropland-use intensity across Europe using MODIS NDVI time series." In: *Environmental Research Letters* 11.2, p. 024015. ISSN: 1748-9326. DOI: 10.1088/1748-9326/11/2/024015.

Falkenmark, Malin and David Molden (2008). "Wake Up to Realities of River Basin Closure." In: *International Journal of Water Resources Development* 24.2, pp. 201–215. DOI: 10.1080/07900620701723570.

Flach, Rafaela, Ylva Ran, Javier Godar, Louise Karlberg, and Clement Suavet (2016). "Towards more spatially explicit assessments of virtual water flows: linking local water use and scarcity to global demand of Brazilian farming commodities." In: *Environmental Research Letters* 11.7, p. 075003. ISSN: 1748-9326. DOI: 10.1088/1748-9326/11/7/075003.

Foley, J. A. (2005). "Global Consequences of Land Use." In: *Science* 309.5734, pp. 570–574. ISSN: 0036-8075. DOI: 10.1126/science.1111772. arXiv: arXiv:1011.1669v3.

Gibbs, H. K., L Rausch, J Munger, I Schelly, D C Morton, P Noojipady, B. Soares-Filho, P Barreto, L Micol, and N F Walker (2015). "Brazil's Soy Moratorium." In: *Science* 347.6220, pp. 377–378. ISSN: 0036-8075. DOI: 10.1126/science.aaa0181.

Gibbs, H. K., A. S. Ruesch, F. Achard, M. K. Clayton, P. Holmgren, N. Ramankutty, and J. A. Foley (2010). "Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s." In: *Proceedings of the National Academy of Sciences* 107.38, pp. 16732–16737. ISSN: 0027-8424. DOI: 10.1073/pnas.0910275107.

Godar, Javier, U. Martin Persson, Emilio Jorge Tizado, and Patrick Meyfroidt (2015). "Towards more accurate and policy relevant footprint analyses: Tracing fine-scale socio-environmental impacts of production to consumption." In: *Ecological Economics* 112, pp. 25–35. ISSN: 09218009. DOI: 10.1016/j.ecolecon.2015.02.003.

Hanasaki, Naota, Toshiyuki Inuzuka, Shinjiro Kanae, and Taikan Oki (2010). "An estimation of global virtual water flow and sources of water withdrawal for major crops and livestock products using a global hydrological model." In: *Journal of Hydrology* 384.3-4, pp. 232–244. ISSN: 00221694. DOI: 10.1016/j.jhydrol.2009.09.028.

Hargreaves, George H. and Zohrab A. Samani (1985). "Reference Crop Evapotranspiration from Temperature." In: *Applied Engineering in Agriculture* 1.2, pp. 96–99. ISSN: 1943-7838. DOI: 10.13031/2013.26773.

Hengl, Tomislav et al. (2014). "SoilGrids1km — Global Soil Information Based on Automated Mapping." In: *PLoS ONE* 9.8. Ed. by Ben Bond-Lamberty, e105992. ISSN: 1932-6203. DOI: 10.1371/journal.pone.0105992.

Hoff, H., M. Falkenmark, D. Gerten, L.J. Gordon, L. Karlberg, and J. Rockström (2010). "Greening the global water system." In: *Journal of Hydrology* 384.3-4, pp. 177–186. ISSN: 00221694. DOI: 10.1016/j.jhydrol.2009.06.026.

Hunke, Philip, Eva Nora Mueller, Boris Schröder, and Peter Zeilhofer (2015). "The Brazilian Cerrado: Assessment of water and soil degradation in catchments under intensive agricultural use." In: *Ecohydrology* 8.6, pp. 1154–1180. ISSN: 19360592. DOI: 10.1002/eco.1573.

IBGE (Brazilian Institute of Geography and Statistics) (2018). *Levantamento Sistemático da Produção Agrícola*. URL: https://sidra.ibge.gov.br/tabela/6588 (visited on 12/13/2018).

Jarvis, A., H.I. Reuter, A. Nelson, and E. Guevara (2008). *Hole-filled SRTM for the globe Version 4, available from the CGIAR-CSI SRTM 90m Database.* Tech. rep. CGIAR. URL: http://srtm.csi.cgiar.org.

Keys, Patrick W., Lan Wang-Erlandsson, and Line J. Gordon (2016). "Revealing Invisible Water: Moisture Recycling as an Ecosystem Service." In: *PLOS ONE* 11.3. Ed. by Gary Stuart Bilotta, e0151993. ISSN: 1932-6203. DOI: 10.1371/journal.pone.0151993.

Lathuillière, Michael, Michael Coe, Andrea Castanho, Jordan Graesser, and Mark Johnson (2018b). "Evaluating Water Use for Agricultural Intensification in Southern Amazonia Using the Water Footprint Sustainability Assessment." In: *Water* 10.4, p. 349. ISSN: 2073-4441. DOI: 10.3390/w10040349.

Liu, Junguo and Hong Yang (2010). "Spatially explicit assessment of global consumptive water uses in cropland: Green and blue water." In: *Journal of Hydrology* 384.3-4, pp. 187–197. ISSN: 00221694. DOI: 10.1016/j.jhydrol.2009.11.024.

Marengo, J A, C A Nobre, S C Chou, J Tomasella, G Sampaio, L M Alves, G O Obregón, W R Soares, R Betts, and G Kay (2011). "Dangerous Climate Change in Brazil." In: p. 56.

Mekonnen, M. M. and a. Y. Hoekstra (2011). "The green, blue and grey water footprint of crops and derived crop products." In: *Hydrology and Earth System Sciences* 15.5, pp. 1577–1600. ISSN: 1607-7938. DOI: 10.5194/hess-15-1577-2011.

Pires, Gabrielle F., Gabriel M. Abrahão, Livia M. Brumatti, Leydimere J.C. Oliveira, Marcos H. Costa, Spencer Liddicoat, Etsushi Kato, and Richard J. Ladle (2016). "Increased climate risk in Brazilian double cropping agriculture systems: Implications for land use in Northern Brazil." In: *Agricultural and Forest Meteorology* 228-229, pp. 286–298. issn: 01681923. doi: 10.1016/j.agrformet.2016.07.005.

Quinteiro, Paula, Ana Cláudia Dias, Margarida Silva, Bradley G. Ridoutt, and Luís Arroja (2015). "A contribution to the environmental impact assessment of green water flows." In: *Journal of Cleaner Production* 93, pp. 318–329. issn: 09596526. doi: 10.1016/j.jclepro.2015.01.022.

Ray, Deepak K. and Jonathan A. Foley (2013). "Increasing global crop harvest frequency: Recent trends and future directions." In: *Environmental Research Letters* 8.4. issn: 17489326. doi: 10.1088/1748-9326/8/4/044041.

Ridoutt, Bradley G. and Stephan Pfister (2010). "A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity." In: *Global Environmental Change* 20, pp. 113–120. issn: 09593780. doi: 10.1016/j.gloenvcha.2009.08.003.

Rockström, Johan and Jennie Barron (2007). "Water productivity in rainfed systems: Overview of challenges and analysis of opportunities in water scarcity prone savannahs." In: *Irrigation Science* 25.3, pp. 299–311. issn: 03427188. doi: 10.1007/s00271-007-0062-3.

Sacks, William J., Delphine Deryng, Jonathan A. Foley, and Navin Ramankutty (2010). "Crop planting dates: An analysis of global patterns." In: *Global Ecology and Biogeography* 19.5, pp. 607–620. issn: 1466822X. doi: 10.1111/j.1466-8238.2010.00551.x.

Schyns, J. F., A. Y. Hoekstra, and M. J. Booij (2015). "Review and classification of indicators of green water availability and scarcity." In: *Hydrology and Earth System Sciences Discussions* 12.6, pp. 5519–5564. issn: 1812-2116. doi: 10.5194/hessd-12-5519-2015.

Schyns, Joep F, Arjen Y Hoekstra, Martijn J Booij, Rick J Hogeboom, and Mesfin M Mekonnen (2019). "Limits to the world's green water resources for food, feed, fiber, timber, and bioenergy." In: *Proceedings of the National Academy of Sciences* 116.11, pp. 4893–4898. issn: 0027-8424. doi: 10.1073/pnas.1817380116.

Siebert, Stefan and Petra Döll (2010). "Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation." In: *Journal of Hydrology* 384.3-4, pp. 198–217. issn: 00221694. doi: 10.1016/j.jhydrol.2009.07.031.

Siebert, Stefan, Felix T. Portmann, and Petra Döll (2010). "Global patterns of cropland use intensity." In: *Remote Sensing* 2.7, pp. 1625–1643. issn: 20724292. doi: 10.3390/rs2071625.

Silva, Vicente de Paulo R. da et al. (2016b). "Water footprint and virtual water trade of brazil." In: *Water (Switzerland)* 8.11. issn: 20734441. doi: 10.3390/w8110517.

Spera, Stephanie A., Gillian L. Galford, Michael T. Coe, Marcia N. Macedo, and John F. Mustard (2016). "Land-use change affects water recycling in Brazil's last agricultural frontier." In: *Global Change Biology* 22.10, pp. 3405–3413. issn: 13541013. doi: 10.1111/gcb.13298.

Tuninetti, Marta, Stefania Tamea, Paolo D'Odorico, Francesco Laio, and Luca Ridolfi (2015). "Global sensitivity of high-resolution estimates of crop water footprint." In: *Water Resources Research* 51.10, pp. 8257–8272. issn: 19447973. doi: 10.1002/2015WR017148.

Tuninetti, Marta, Stefania Tamea, Francesco Laio, and Luca Ridolfi (2017). "A Fast Track approach to deal with the temporal dimension of crop water footprint." In: *Environmental Research Letters* 12.7. ISSN: 17489326. DOI: 10.1088/1748-9326/aa6b09.

Wada, Yoshihide and Marc F P Bierkens (2014). "Sustainability of global water use: past reconstruction and future projections." In: *Environmental Research Letters* 9.10, p. 104003. ISSN: 1748-9326. DOI: 10.1088/1748-9326/9/10/104003.

Wu, Wenbin, Qiangyi Yu, Liangzhi You, Kevin Chen, Huajun Tang, and Jianguo Liu (2018). "Global cropping intensity gaps: Increasing food production without cropland expansion." In: *Land Use Policy* 76.February, pp. 515–525. ISSN: 02648377. DOI: 10.1016/j.landusepol.2018.02.032.

Xavier, Alexandre C., Carey W. King, and Bridget R. Scanlon (2016). "Daily gridded meteorological variables in Brazil (1980-2013)." In: *International Journal of Climatology* 36.6, pp. 2644–2659. ISSN: 08998418. DOI: 10.1002/joc.4518. arXiv: 1311.1716.

Yan, Huimin, Xiangming Xiao, Heqing Huang, Jiyuan Liu, Jingqing Chen, and Xuehong Bai (2014). "Multiple cropping intensity in China derived from agro-meteorological observations and MODIS data." In: *Chinese Geographical Science* 24.2, pp. 205–219. ISSN: 1993064X. DOI: 10.1007/s11769-013-0637-2.

Zalles, Viviana et al. (2019). "Near doubling of Brazil's intensive row crop area since 2000." In: *Proceedings of the National Academy of Sciences* 116.2, pp. 428–435. ISSN: 0027-8424. DOI: 10.1073/pnas.1810301115.

Zhao, Yan, Linyan Bai, Jianzhong Feng, Xiaosong Lin, Li Wang, Lijun Xu, Qiyun Ran, and Kui Wang (2016). "Spatial and Temporal Distribution of Multiple Cropping Indices in the North China Plain Using a Long Remote Sensing Data Time Series." In: *Sensors* 16.4, p. 557. ISSN: 1424-8220. DOI: 10.3390/s16040557.

APPENDICES

A

APPENDIX TO CHAPTER 2

A.1 EXTENDED METHODS

A.1.1 *Simulation unit delimitation*

We first classified the territory in Homogeneous Response Units (HRUs), by classifying the biophysical properties of soil texture, elevation and slope were based on the thresholds presented in Table A.1. The HRU delimitation and the thresholds used in this study are inspired by the methodology used in the development of the GEOBENE database (Skalský et al., 2008).

The elevation raster was obtained from the NASA Shuttle Radar Topographic Mission (SRTM) 90m Digital Elevation Database (v4.1), available through the Consortium for Spatial Information (CGIAR-CSI) of the Consultative Group for International Agricultural Research (CGIAR) (Jarvis et al., 2008), with a resolution of 90m at the equator. Soil texture was calculated with the use of the R package soil texture, with granulometry input from the SoilGrids Global Soil Information Based on Automated Mapping (Hengl et al., 2014).

To achieve the final delimitation of the study's simulation units, we further divided the HRUs based on municipal boundaries, land use, and climate patterns. The polygons with the classes of slope, soil and elevation were overlaid with these three other polygons.

The municipal delimitation was obtained from the Brazilian Statistics and Geography Institute (IBGE), and represents the municipal boundaries in Brazil in 2010. The climate grid represents the size of the grid cells of the climate database from Xavier, King, and Scanlon (2016).

Table A.1: Classes of elevation, slope and soil texture used for delimitation of the homogeneous response units in this study.

Elevation classes (m)	<300
	300-600
	600-1100
	1100-1600
	1600-2100
	>2100
Slope classes (%)	<3
	3-6
	6-10
	10-15
	15-30
	30-50
	>50
Soil Texture	Coarse
	Medium
	Fine

The land use mask was obtained with the use of the European Space Agency's Climate Change Initiative Land Cover Maps (ESA-CCI LC maps) (ESA, 2017), and the data on harvested area per Brazilian municipality from the Brazilian Statistics Bureau (IBGE) for around all municipalities and all crops of interest, between 1990 and 2013. First, we re-classified the ESA-CCI LC maps between cropland and non-cropland areas, and we obtained a land use mask in which only pixels with presence of cropland between 1990 and 2013 were considered in the study. Furthermore, the IBGE municipal harvested area enabled the identification of the municipalities where production of each crop happened between 1990 and 2013. Only simulation units in municipalities where these crops were produced during this period were included in the model runs.

A.1.2 *Calculation of potential heat units*

Potential heat units (PHU) correspond to the total number of heat units or growing degree days needed to bring the plant from emergence to physiological maturity. Heat units are calculated as the difference between the average of the daily maximum and minimum temperatures and a certain base temperature, above which the plants start to grow. This base temperature varies between crops. We calculated the PHUs per simulation unit as the average of the accumulated heat units from harvesting to planting, throughout the 24 simulated cropping seasons.

$$HeatUnits = \frac{T_{Max} - T_{Min}}{2} - T_{Base} \tag{A.1}$$

$$PotentialHeatUnits = \left(\sum_{i=1980}^{2014} \sum_{j=PlantingDate}^{HarvestingDate} HeatUnits_{i,j} \right) / 24 \tag{A.2}$$

A.1.3 *Selection of crop calendars and generation of new soil files*

Ultimately, the objective of the EPIC model simulations is to provide us with estimation of consumptive water use and yields for different scenarios of agricultural management – in this case, irrigation and fertilization scenarios. Before the final model simulations, we designed two preliminary steps to remove some uncertainties related to the crop calendar options and soil nutrient depletion.

The database available in Sacks et al. (2010) present early and late planting and harvesting dates for all crops, for different zones in the territory. We ran three model runs for crop calendars in early, late and mid planting and harvesting seasons, and selected the calendar option for each simulation unit that resulted in the highest average yields.

The spin-up runs are supposed to equilibrate the nutrient pools in the soil. We summarized the general structure of the model setup in Table A.2, and further described below:

1. Calendar runs. We applied these model runs for selection of optimal crop calendars for each simulation unit. The setup options are non-irrigated, with full fertilization, and static soil profile. The average yield for each SimU is calculated, and the crop calendar option with the highest average yield is chosen. Run performed between 1990 and 2013.

2. Soil file runs. Are rainfed, with low fertilization input, and dynamic soil profile. In these runs, we generate new soil files with soil organic carbon and nutrient pools balanced with low nutrient input management. Run performed between 1980 and 1990.

3. Final scenario runs. The final scenario runs were set up with different fertilizer and irrigated water application rates. For nitrogen application, the model was set to provide nitrogen when nitrogen stress is above 20% (nitrogen trigger of 0.8), with a pre-determined application rate specific to each scenario. When it comes to phosphorus, the model was set to apply a certain application rate before planting. Table A.3 summarizes the fertilization application rates for phosphorus and nitrogen used in the model scenarios. The irrigated scenario was modeled to provide irrigation when the water stress factor, defined by the soil water stored divided by total plant available water storage) is above 80%, with the application rate to supply the necessary irrigation to eliminate water stress, as seen in Table A.4.

Table A.2: General structure of the three model setups.

Run	Soil	Fertilization
Calendar	Static	High-Input
Spin-Off Soil	Dynamic	Low-Input
Scenario	Static	All scenarios (as specified in Table A.3)

Table A.3: Model setup for fertilization scenarios.

Scenario	N Fertilizer trigger	N Application rate (kg/ha)	P application rate – Other crops (kg/ha)	P application rate-Soybeans (kg/ha)
Subsistence	0	0	0.1	0.1
Low-Input	0.8	25	25	10
Mid-Input	0.8	100	100	30
High-Input	0.8	400	400	400

Table A.4: Model setup for irrigation scenarios.

Scenario	Irrigation trigger	Irrigation application rate (mm)
Non-irrigated	0	0
Irrigated	0.8	2000 (unlimited)

A.2 MODEL EVALUATION

We compared the simulated yields and with the reported yields obtained from the Brazilian Institute for Geography and Statistics (IBGE, 2019) between 1990 and 2013 (see Figures S1-S5, bottom). The model reproduces the range of possible outcomes when it comes to agricultural management, for most crops and regions. The model tends to represent better the values on the higher end of the spectrum, failing in general to represent historically low reported yields, particularly in the Northeast region of the country. On the higher end of the spectrum, however, our results seem to represent the yield potential better than previous estimates; the reported yields in the five most productive municipalities in 2013 (Table A.5) are more coherent with the values estimated in this study (Table A.6) than previously reported (Table A.7).

Our model does not reproduce all processes that could explain abnormally low yields, such as pests, diseases, windstorms, and other factors, which may contribute to the general over-estimation in the model. The model performs better in crops and regions with higher homogeneity. Maize is the crop that grows in a larger number of municipalities across the country and presents a greater range of management options that are not always parameterized in the model. On the other side, regions with low production levels of a certain crop appear to be more divergent due to a smaller sample size, as the reported yields tend to be less reliable in these cases. One example of this is the wheat production in the central-west region, which is responsible for only approximately 4% of the country's total wheat production (see Figure A.5).

We observed that the potential yields per crop estimated in this study for the high-input runs, both under irrigated and water-stressed conditions, are similar to previously published estimates. However, the average high-input non-irrigated yields for cotton and soybeans estimated in this study (5.1 and 3.6 ton/ha, respectively) are much higher than the potential yields estimated in Mueller et al. (2012) (2.8 and 2.9 ton/ha, respectively), which are based on statistics around the year 2000 (Table A.6-Table A.7). When compared to these previous results, our potential yields for wheat are conservative, while the opposite is true for cotton and soybeans. However, when considering the cotton and soybean yields measured in Brazil in the year 2013 in the five most productive municipalities (4.65 and 5.4 ton/ha, respectively), we can argue that our results show a better representation of the potential of these crops in Brazil (Table A.5-Table A.6).

We also compared the simulated water productivity and consumptive water use estimated by our model with previously reported results in the water footprint literature (Table A.8-Table A.11).

The range of water productivity and consumptive water use for each crop estimated in this study is also similar to values found in previous water footprint studies (Lathuillière, 2011; Liu and Yang, 2010; Mekonnen and Hoekstra, 2011). The water footprints assessment for crops worldwide in the period 1996-2005 carried out by Mekonnen and Hoekstra (2011) obtained values of consumptive water use values for crops in Brazil that roughly correspond to the values between the low and mid-input scenarios estimated in this study.

Table A.5: Historical yields in Brazil for the crops analyzed in this study, according to IBGE (Brazilian Institute of Geography and Statistics) (2018)

Scenario	Cotton	Maize	Soybean	Wheat
1990, region range	0.45-1.17	0.3-2.48	0.6-1.87	1.06-1.17
1990, region average	1.17	1.66	1.43	1.11
2010, region range	2.05-3.61	1.7-5.73	2.84-3.04	2.68-2.84
2010, region average	3.14	3.94	2.91	2.63
2013, 5 most productive municipalities	4.65	13.33	5.4	5.74

Table A.6: Average yields (ton/ha) estimated in this study, for every crop and scenario.

Scenario	Cotton	Maize	Maize 2^{nd} season	Soybean	Wheat
Subsistence	1.2	2.5	2.6	1.0	0.6
Low Input	1.9	3.4	3.4	1.9	1.4
Mid-input	3.9	5.5	5.0	3.43	2.7
Mid-input irrigated	4.1	6.2	5.9	3.7	2.8
High -input	5.1	6.0	5.3	3.6	2.8
High-input irrigated	5.9	6.8	6.4	3.9	2.9

Table A.7: Potential yields estimated in Mueller et al. (2012).

Brazil	Cotton	Maize	Soybean	Wheat
year 2000-within climate bins (Monfreda, Ramankutty, and Foley, 2008)	2.25	3.04	2.5	2.32
yield gaps closed to 50% AY	2.31	3.35	2.5	2.43
yield gaps closed to 75% AY	2.48	4.01	2.54	3.03
yield gaps closed to 90% AY	2.71	4.62	2.67	3.6
yield gaps closed to 100% AY	2.92	5.08	2.88	4
attainable yield (t/ha-avg across area of interest)	2.84	5.06	2.87	4
World				
year 2000-within climate bins (Monfreda, Ramankutty, and Foley, 2008)	1.7	4.53	2.24	2.73
yield gaps closed to 50% AY	1.84	5.06	2.28	3.04
yield gaps closed to 75% AY	2.16	5.99	2.41	3.72
yield gaps closed to 90% AY	2.44	6.78	2.6	4.26
yield gaps closed to 100% AY	2.66	7.42	2.81	4.67
attainable yield (t/ha-avg across area of interest)	2.65	7.39	2.81	4.64

Table A.8: Consumptive water use (m^3/ton) and water productivity (kg/m^3) estimated in this study for every crop and scenario, maximum and minimum values for regional averages.

Scenario	Cotton	Maize	Maize 2^{nd} season	Soybean	Wheat
Consumptive water use (m^3/ton), regional range					
Subsistence	3683-6539	1591-2620	869-166	2682-6538	3398-5429
Low Input	2532-3998	1121-1882	748-1128	1679-2967	1613-2564
Mid-input	1161-1874	803-1082	572-648	1360-1507	903-1181
Mid-input irrigated	1481-1926	955-1090	558-650	1348-1508	888-1215
High-input	970-1309	800-959	546-644	1341-1428	901-1181
High-input irrigated	1006-1338	832-974	508-645	1578-2138	887-1183
Water productivity (kg/m^3), regional range					
Subsistence	0.09-0.17	0.38-0.63	0.6-1.15	0.15-0.37	0.18-0.29
Low Input	0.16-0.24	0.53-0.89	0.89-1.34	0.34-0.6	0.39-0.62
Mid-input	0.33-0.53	0.92-1.24	1.54-1.75	0.66-0.74	0.85-1.11
Mid-input irrigated	0.32-0.42	0.92-1.05	1.54-1.79	0.66-0.74	0.82-1.13
High-input	0.47-0.64	1.04-1.25	1.55-1.83	0.70-0.75	0.85-1.11
High-input irrigated	0.46-0.62	1.03-1.2	1.55-1.97	0.47-0.63	0.85-1.13

Table A.9: Consumptive water use (m^3/ton) and water productivity (kg/m^3) values from Lathuillière (2011).

	Cotton	Maize	Soybean
Consumptive water use (m^3/ton), range			
State of Mato Grosso, potential values	1130-1160	720-790	1070-2140
State of Mato Grosso, actual values	610-740	510-670	1530-1750
Tropical	2080-2160	940-1460	1250-1960
Global	1670-2500	625-1250	1430-2500
Water productivity (kg/m^3), range			
State of Mato Grosso, potential values	0.88-0.86	1.39-1.27	0.93-0.47
State of Mato Grosso, actual values	1.64-1.35	1.96-1.49	0.65-0.57
Tropical	0.48-0.46	1.06-0.68	0.8-0.51
Global	0.6-0.4	1.6-0.8	0.7-0.4

Table A.10: Values from Mekonnen and Hoekstra (2011).

	Cotton	Maize	Soybeans	Wheat
Consumptive water use (m^3/ton) (1996-2005)				
Global average	2282	947	2037	1277
Brazil, country average	2208	1621	2181	1989
Brazil, range per state	1514-3006	1163-2544	1628-2544	885-4230
Water productivity (kg/m^3) (1996-2005)				
Global average	0.45	0.62	0.46	0.5
Brazil, country average	0.44	1.06	0.49	0.78
Brazil, range per state	0.66-0.33	0.86-0.39	0.61-0.39	1.13-0.24

Table A.11: Values estimated in Liu, Zehnder, and Yang (2009).

	Maize	Wheat
Consumptive water use (m^3/ton)		
South America	693.96	2518.89
World	701.75	1075.27
Water productivity (kg/m^3)		
South America	1.441	0.397
World	1.425	0.93

A.3 Extended results

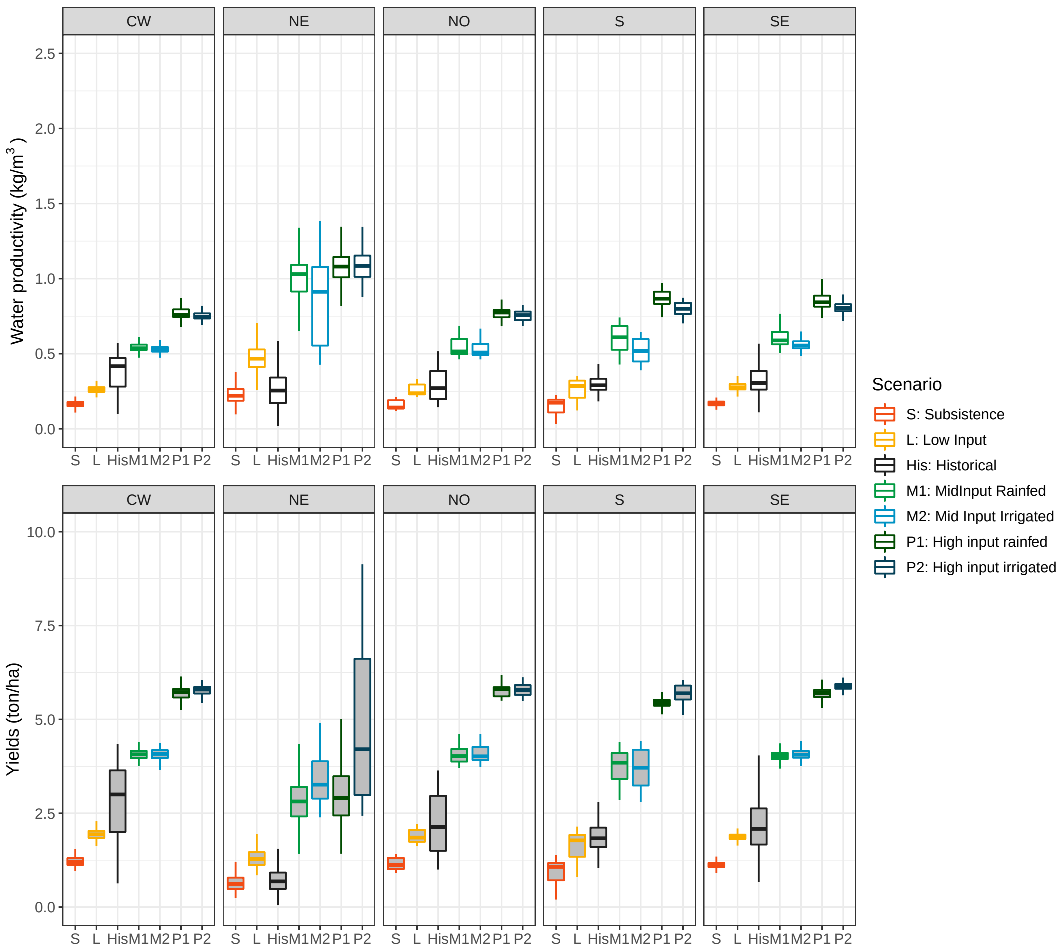


Figure A.1: Yields (below, ton/ha) and water productivity (above, kg/m^3) statistics per municipality, related to historical data and management scenarios, for cotton

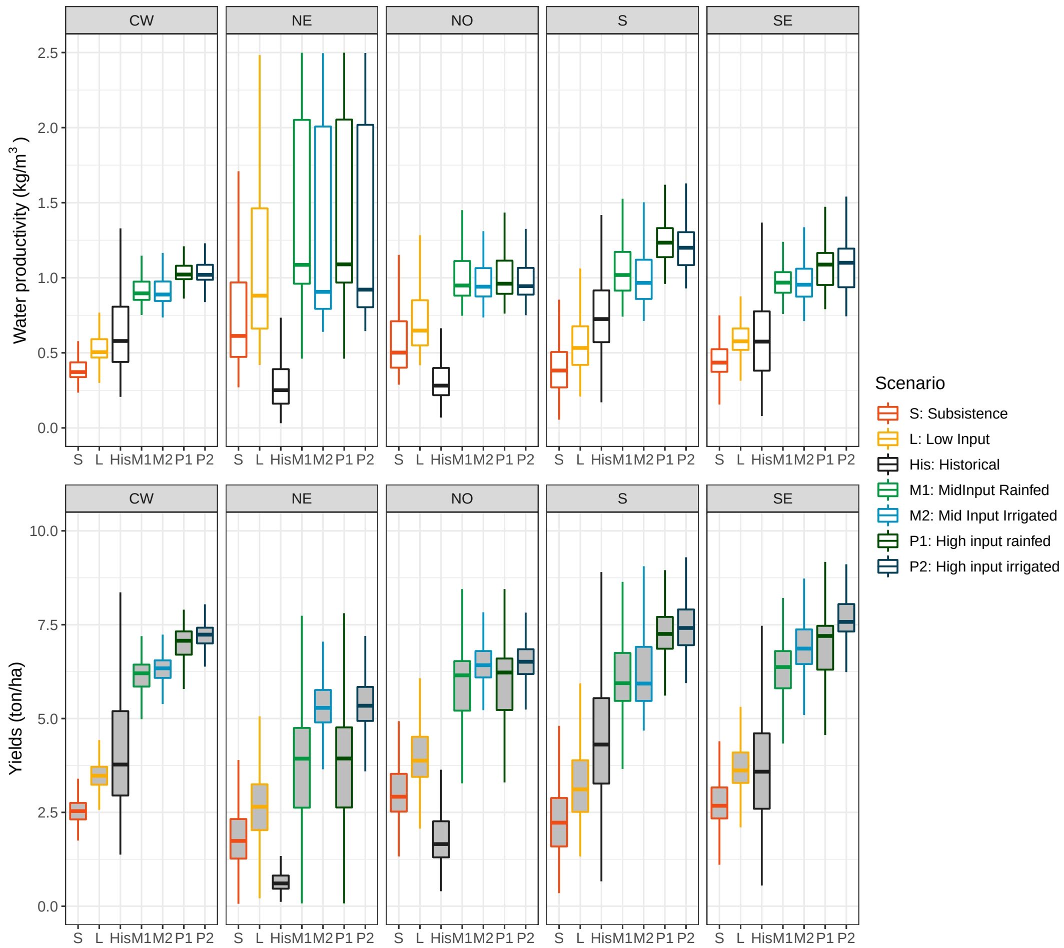


Figure A.2: Yields (below, ton/ha) and water productivity (above, kg/m^3) statistics per municipality, related to historical data and management scenarios, for maize

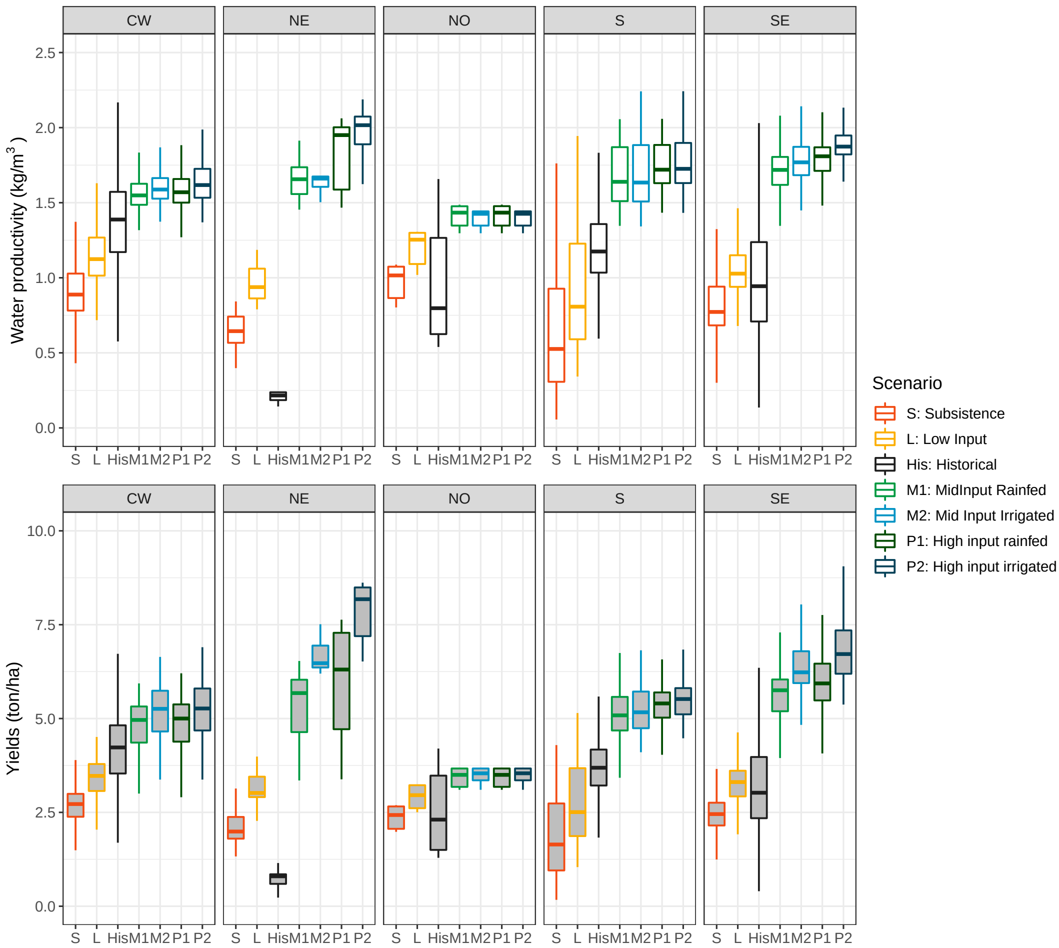


Figure A.3: Yields (below, ton/ha) and water productivity (above, kg/m^3) statistics per municipality, related to historical data and management scenarios, for maize second season

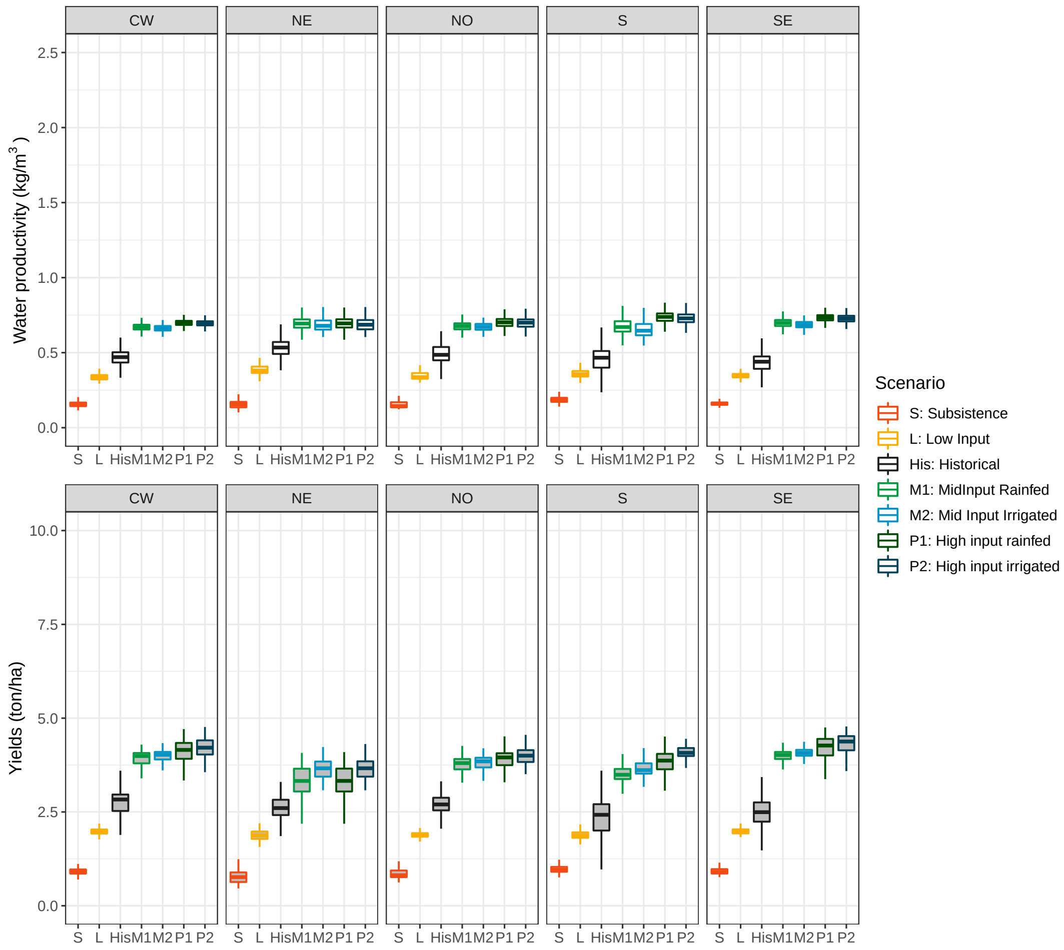


Figure A.4: Yields (below, ton/ha) and water productivity (above, kg/m^3) statistics per municipality, related to historical data and management scenarios, for soybeans

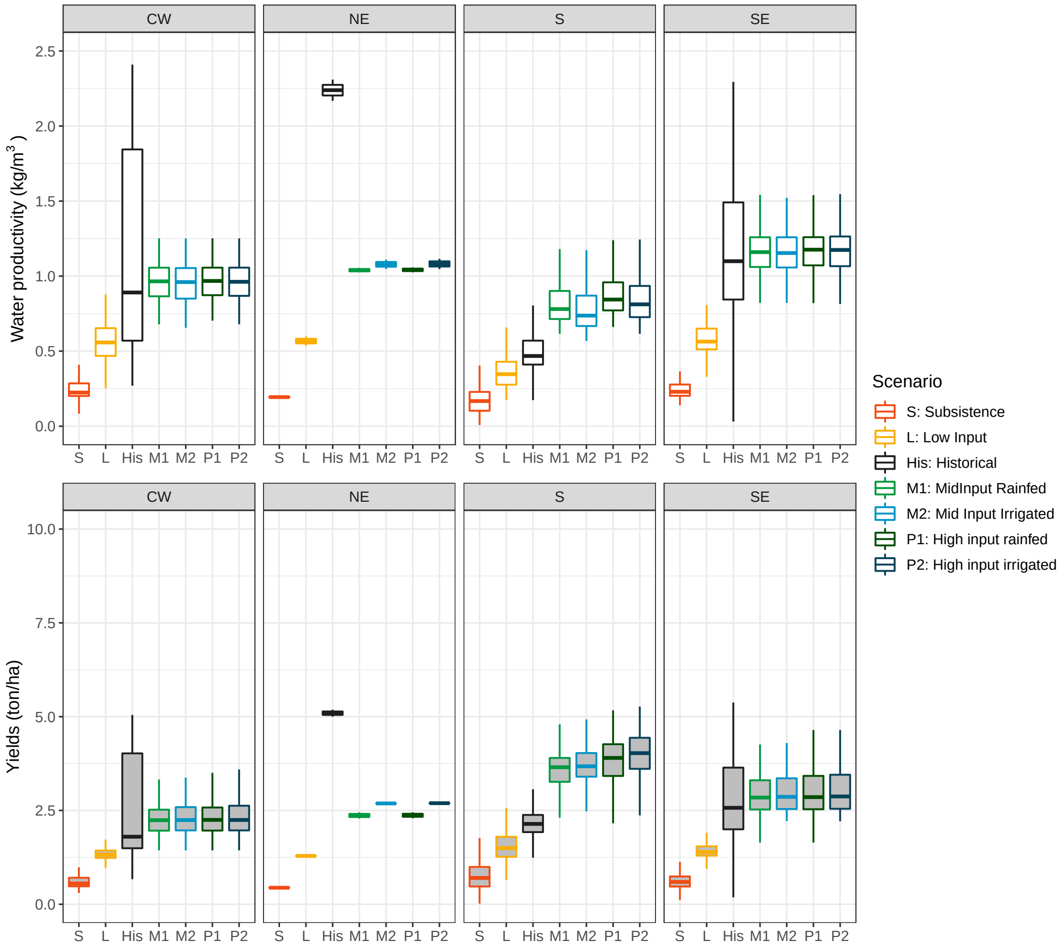


Figure A.5: Yields (below, ton/ha) and water productivity (above, kg/m^3) statistics per municipality, related to historical data and management scenarios, for wheat

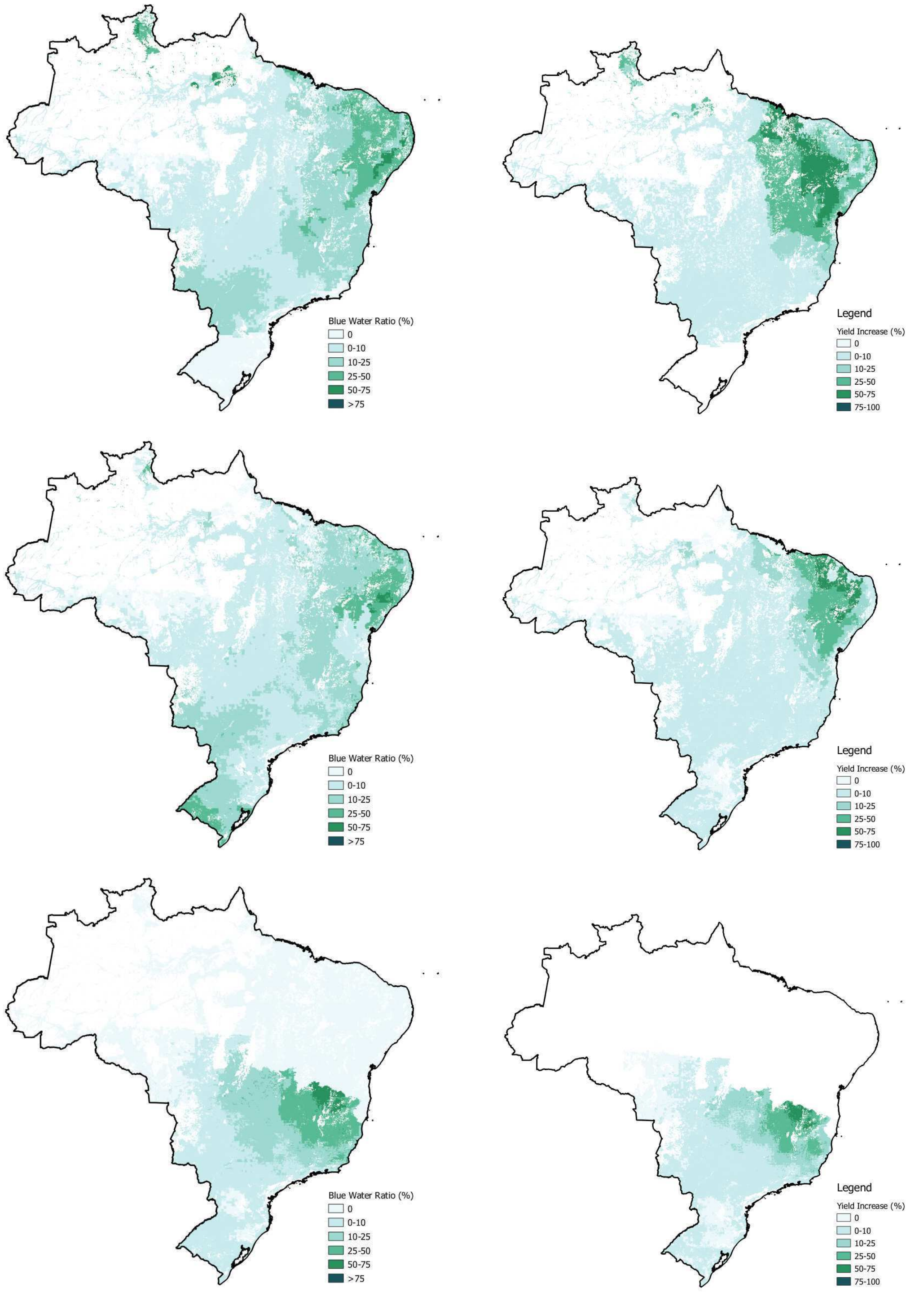


Figure A.6: Ratio between Blue and Green water use in the irrigated high-input scenario (left, %) and average yield increase from water-stressed to irrigated high-input scenario (right, %) for cotton (above), maize (middle) and maize second season (below).

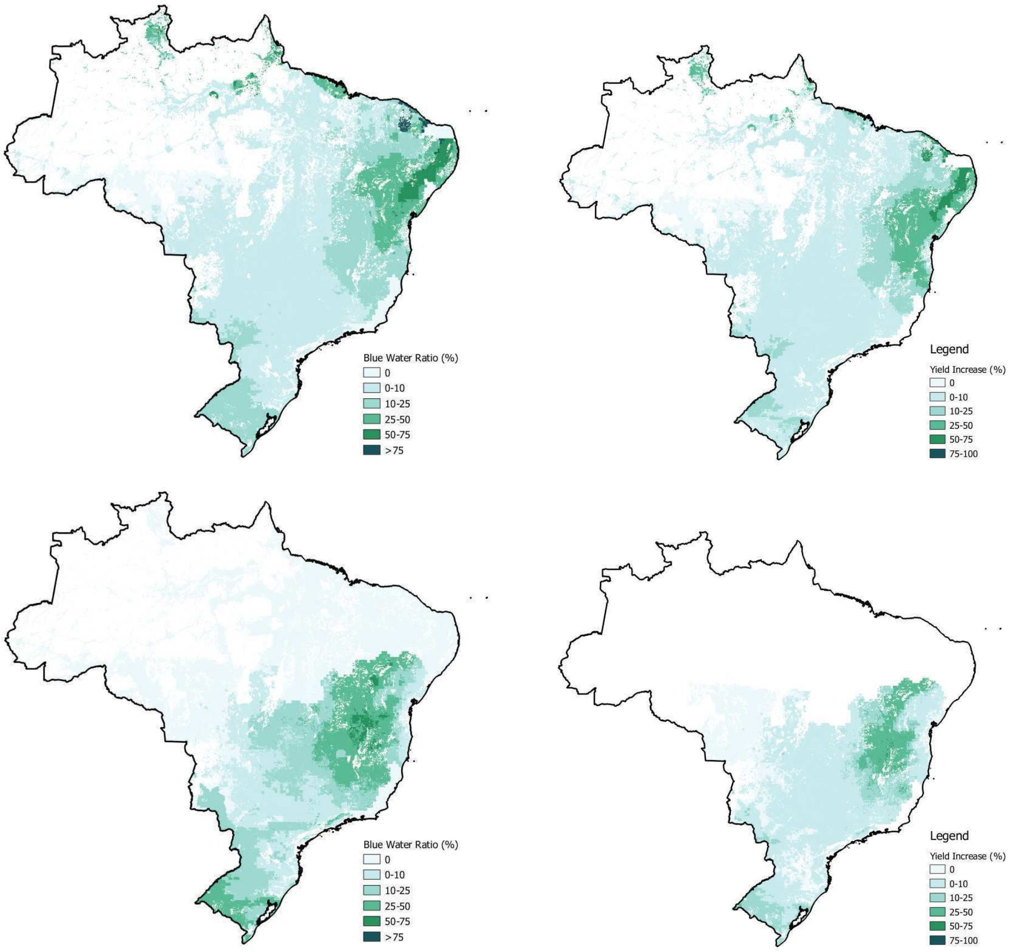


Figure A.7: Ratio between Blue and Green water use in the irrigated high-input scenario (left, %) and average yield increase from water-stressed to irrigated high-input scenario (right, %) for soybeans (above) and wheat (below).

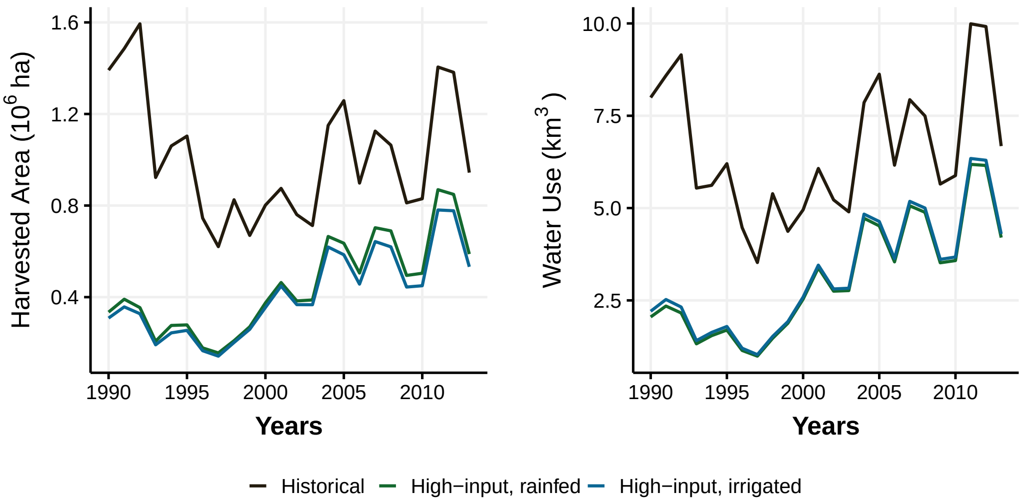


Figure A.8: Annual harvested area ($10^9 ha$) and consumptive water use (km^3) required for production of reported production of cotton between 1990-2013, as well as for the high-input rainfed and irrigated scenarios.

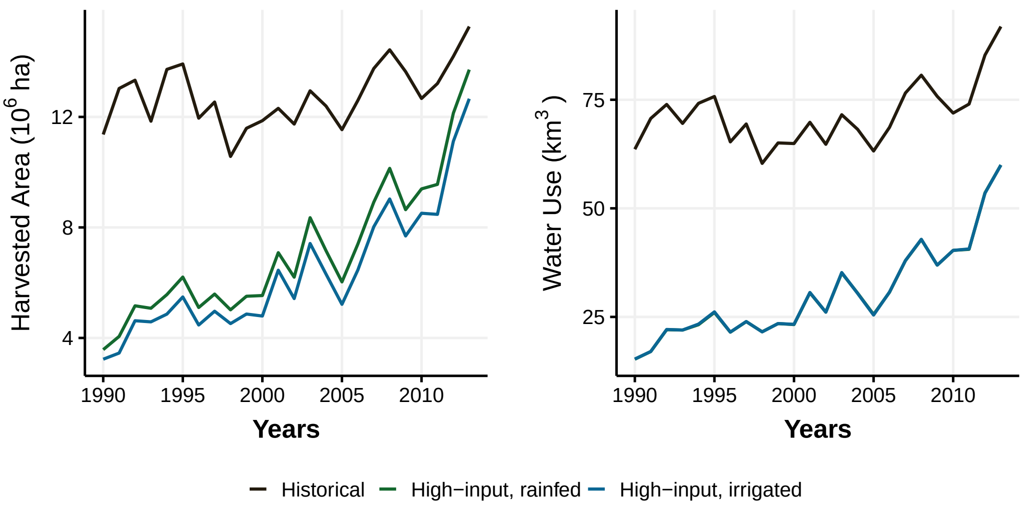


Figure A.9: Annual harvested area ($10^9 ha$) and consumptive water use (km^3) required for production of reported production of maize (composite main and second season) between 1990-2013, as well as for the high-input rainfed and irrigated scenarios.

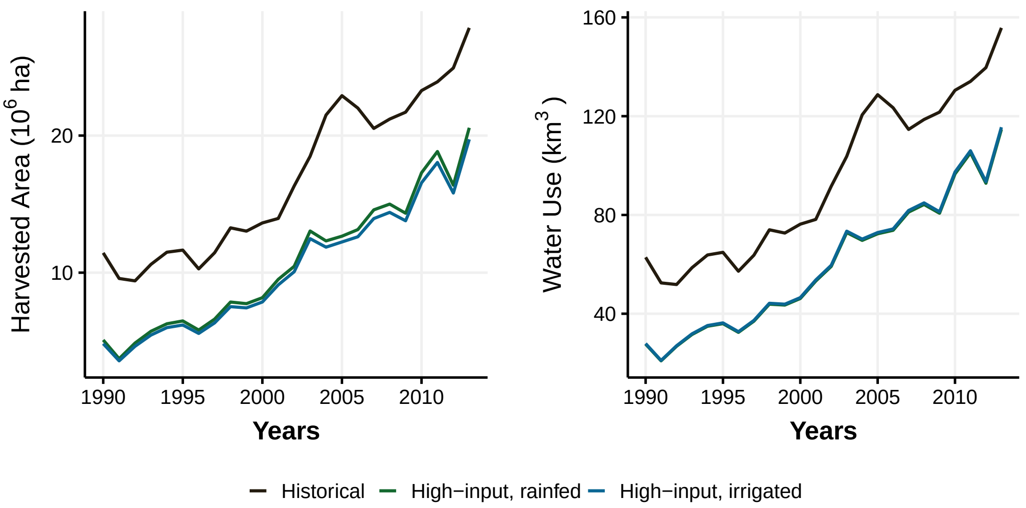


Figure A.10: Annual harvested area ($10^9 ha$) and consumptive water use (km^3) required for production of reported production of soybeans between 1990-2013, as well as for the high-input rainfed and irrigated scenarios.

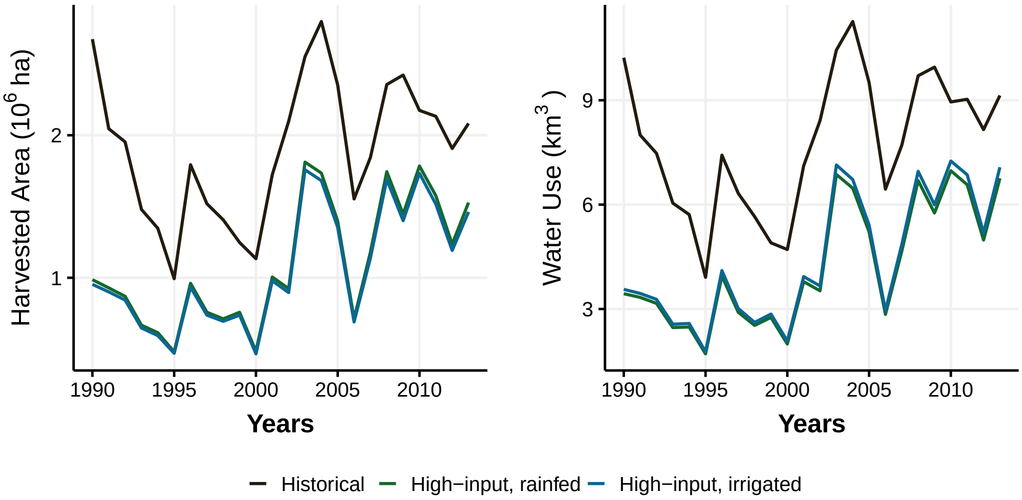


Figure A.11: Annual harvested area ($10^9 ha$) and consumptive water use (km^3) required for production of reported production of wheat between 1990-2013, as well as for the high-input rainfed and irrigated scenarios.

BIBLIOGRAPHY

ESA (2017). *ESA: Land Cover CCI Product User Guide Version 2.0*. Tech. rep. URL: https://www.esa-landcover-cci.org/?q=node/163.

Hengl, Tomislav et al. (2014). "SoilGrids1km — Global Soil Information Based on Automated Mapping." In: *PLoS ONE* 9.8. Ed. by Ben Bond-Lamberty, e105992. ISSN: 1932-6203. DOI: 10.1371/journal.pone.0105992.

IBGE (Brazilian Institute of Geography and Statistics) (2018). *Levantamento Sistemático da Produção Agrícola*. URL: https://sidra.ibge.gov.br/tabela/6588 (visited on 12/13/2018).

Jarvis, A., H.I. Reuter, A. Nelson, and E. Guevara (2008). *Hole-filled SRTM for the globe Version 4, available from the CGIAR-CSI SRTM 90m Database*. Tech. rep. CGIAR. URL: http://srtm.csi.cgiar.org.

Lathuillière, Michael Jacques (2011). "Land use effects on green water fluxes in Mato Grosso, Brazil." Master of Science. University of British Columbia.

Liu, Junguo and Hong Yang (2010). "Spatially explicit assessment of global consumptive water uses in cropland: Green and blue water." In: *Journal of Hydrology* 384.3-4, pp. 187–197. ISSN: 00221694. DOI: 10.1016/j.jhydrol.2009.11.024.

Liu, Junguo, Alexander J.B. B Zehnder, and Hong Yang (2009). "Global consumptive water use for crop production: The importance of green water and virtual water." In: *Water Resources Research* 45.5, pp. 1–15. ISSN: 00431397. DOI: 10.1029/2007WR006051.

Mekonnen, M. M. and a. Y. Hoekstra (2011). "The green, blue and grey water footprint of crops and derived crop products." In: *Hydrology and Earth System Sciences* 15.5, pp. 1577–1600. ISSN: 1607-7938. DOI: 10.5194/hess-15-1577-2011.

Monfreda, Chad, Navin Ramankutty, and Jonathan A. Foley (2008). "Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000." In: *Global Biogeochemical Cycles* 22.1, pp. 1–19. ISSN: 08866236. DOI: 10.1029/2007GB002947.

Mueller, Nathaniel D., James S. Gerber, Matt Johnston, Deepak K. Ray, Navin Ramankutty, and Jonathan A. Foley (2012). "Closing yield gaps through nutrient and water management." In: *Nature* 490.7419, pp. 254–257. ISSN: 00280836. DOI: 10.1038/nature11420. arXiv: NIHMS150003.

Sacks, William J., Delphine Deryng, Jonathan A. Foley, and Navin Ramankutty (2010). "Crop planting dates: An analysis of global patterns." In: *Global Ecology and Biogeography* 19.5, pp. 607–620. ISSN: 1466822X. DOI: 10.1111/j.1466-8238.2010.00551.x.

Skalský, Rastislav, Zuzana Tarasovičová, Juraj Balkovič, Erwin Schmid, Michael Fuchs, Elena Moltchanova, Georg Kindermann, and Peter Scholtz (2008). *GEO-BENE global database for bio-physical modeling v. 1.0*. Tech. rep. Laxenburg, Austria: International Institute for Applied Systems Analysis (IIASA), p. 58.

Xavier, Alexandre C., Carey W. King, and Bridget R. Scanlon (2016). "Daily gridded meteorological variables in Brazil (1980-2013)." In: *International Journal of Climatology* 36.6, pp. 2644–2659. ISSN: 08998418. DOI: 10.1002/joc.4518. arXiv: 1311.1716.

B

Appendix to Chapter 3

B.1 Background data

The changes in water use for the crops analysed in this study are connected to general changes in land use and productivity. Here we visualize data from the Brazilian Institute for Geography and Statistics on soybean and maize (from 1990 to 2013) and main and second season maize (2003 to 2013) for the entire Brazilian territory, and for the states of Mato Grosso and Paraná.

As seen in Figure B.2, in 2013 the two featured states were solely responsible for around half of the country's soybean and maize production. They also present yields higher than the national average, especially for main season maize, as seen in Figure B.3. As shown in Table B.1, the South and Center-West regions are the prominent regions for production of these crops, with the two selected states as their main producers.

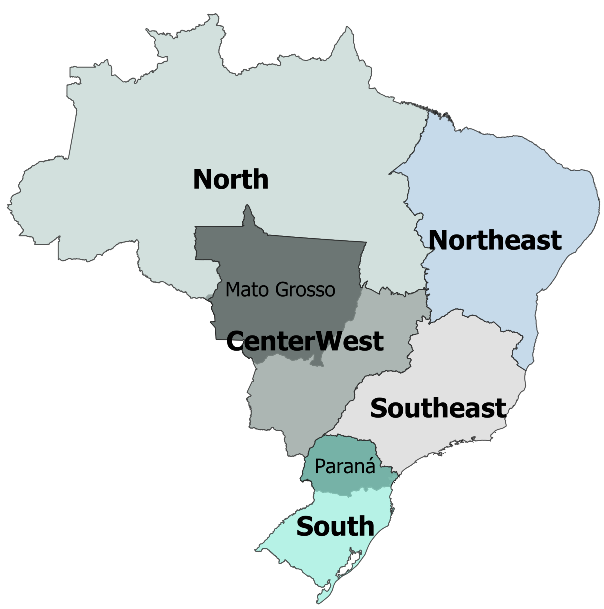


Figure B.1: Distribution of Brazilian macro-regions, and the location of the states of Mato Grosso and Paraná.

Table B.1: Percentage of harvested area of soybeans and maize in different Brazilian macro-regions (%) and total harvested area (ha). These values correspond to the year of 2013, and the data was obtained from the SIDRA database (IBGE (Brazilian Institute of Geography and Statistics), 2018).

	Percentage of total harvested area in each region (%)			
	Soybeans	Maize – single crop	Maize – double crop	Maize
North	3.3	5.9	1.7	3.5
Northeast	8.3	21.7	6.7	12.9
Center-West	46.3	8.6	63.4	40.8
Southeast	6.3	26.4	4.5	13.5
South	35.8	37.3	23.7	29.3
Total Harvested Area (ha)	27,856,702	6,290,498	8,977,925	15,275,225

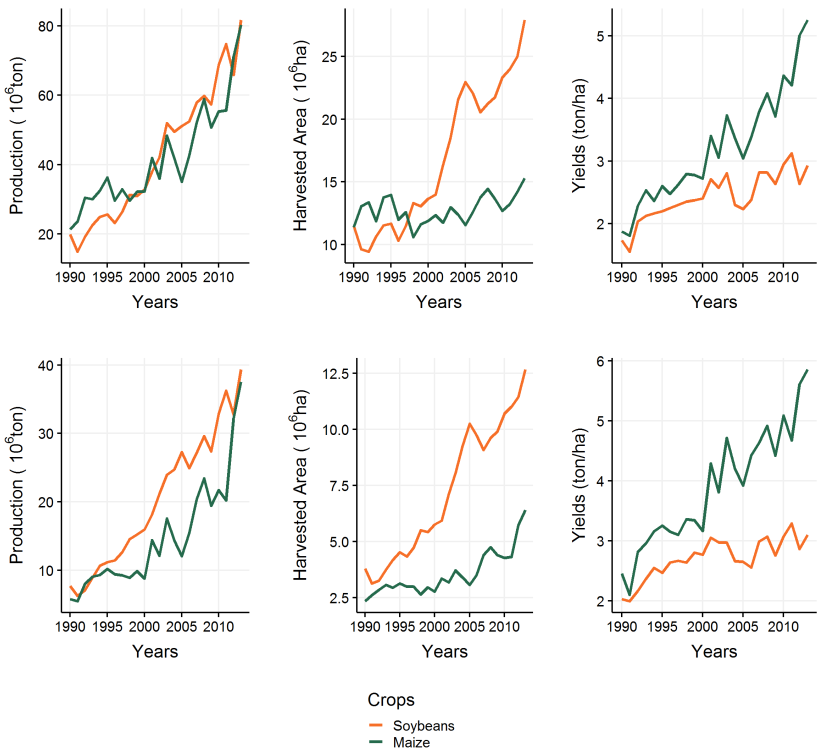


Figure B.2: Evolution of production (10^6 ton, left), harvested area (10^6 ha, center), and yields (ton/ha, right) for soybean and maize in Brazil (above), and in the states of Paraná and Mato Grosso (below). Source: SIDRA database (IBGE (Brazilian Institute of Geography and Statistics), 2018).

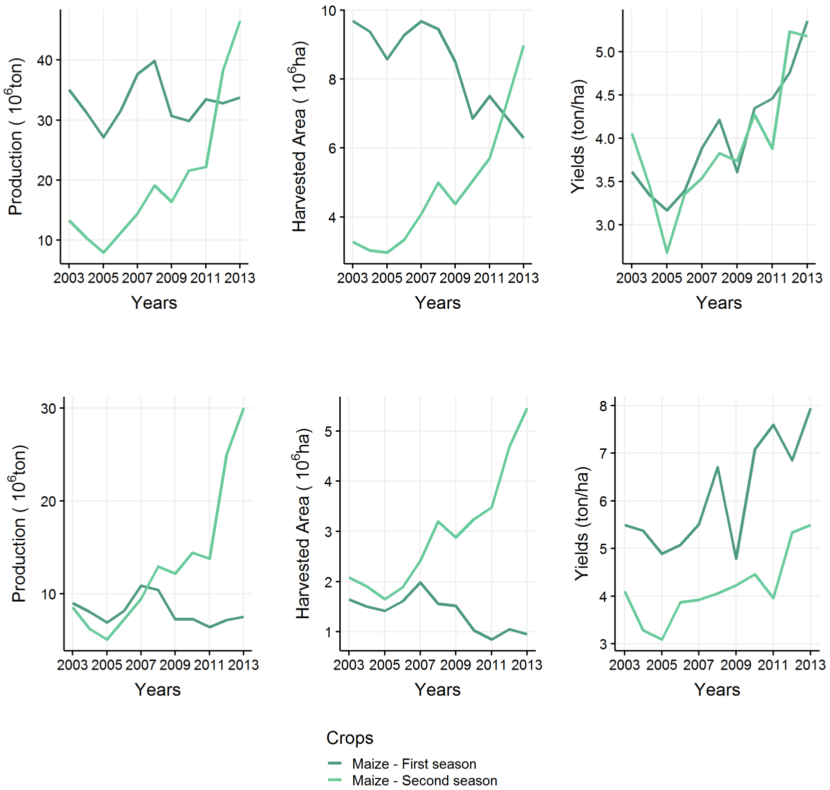


Figure B.3: Evolution of production (10^6 ton, left), harvested area (10^6 ha, center), and yields (ton/ha, right) for maize (main and second season) in Brazil (above), and in the states of Paraná and Mato Grosso (below). Source: SIDRA database (IBGE (Brazilian Institute of Geography and Statistics), 2018).

B.2 EXTENDED METHODS

B.2.1 *Model description*

EPIC is a biophysical model that simulates biological, physical and chemical processes involved in crop growth, operating in daily time steps (Williams, Izaurralde, and Steglich, 2008). The model has been used comprehensively to simulate different aspects related to agriculture and agricultural sustainability, including climate change impacts, nutrient cycling and loss, soil carbon, pesticide fate, consumptive water use, among others (Philip W. Gassman et al., 2004).

EPIC has no spatial component: the model runs independently for land use units that are considered homogeneous for soil, slope, weather, and management. The major components in EPIC are weather, water, erosion-sedimentation, nutrient cycling, pesticide fate, crop growth, soil temperature, tillage, and plant environment control. The model offers options for simulating several other processes - five potential evapotranspiration equations, six erosion/sediment yield equations, two peak runoff rate equations, etc. EPIC can be used to compare management systems and their effects on nitrogen, phosphorus, carbon, pesticides and sediment (Williams et al., 2015).

For this study, the FORTRAN source code of the EPIC 0810 version was compiled and modified for parallel processing in a Linux environment, to make it capable of faster simulations over a large number of simulation units and scenarios.

B.2.2 *Data*

Weather, soil and elevation comprise the set of biophysical data used as input to the EPIC model. For classification of the homogeneous response units we used maps of soil texture, elevation and slope. For the delimitation of the model's simulation units, we overlaid the homogeneous response units with the maps delimitation of municipal boundaries, and the cropland area maps for soybeans in Brazil.

Soil parameters of soil depth, percent sand, silt and clay, bulk density, pH, organic carbon content were obtained from the SoilGrids Global Soil Information Based on Automated Mapping (Hengl et al., 2014). Soil parameters are available for five soil layers (0-5, 5-15, 15-30, 30-60, 60-100 cm), with a resolution of 1 km. The soil hydraulic properties, of saturated water content and saturated water conductivity, were obtained from the HiHydroSoil Soil Map of Hydraulic Properties (Boer, 2015), with a resolution of 1 km.

The topography maps for the area were obtained from the NASA Shuttle Radar Topographic Mission (SRTM) 90m Digital Elevation Database (v4.1), available through the Consortium for Spatial Information (CGIAR-CSI) of the Consultative Group for International Agricultural Research (CGIAR) (Jarvis et al., 2008). The CGIAR-CSI SRTM Digital Elevation Models have a resolution of 90 meters at the equator.

Six daily meteorological variables were used: maximum temperature, minimum temperature, precipitation, wind speed, relative humidity, and solar radiation. These variables were obtained from the database of daily gridded meteorological variables in Brazil between 1980 and 2013 (Xavier, King, and Scanlon, 2016), with a spatial resolution of 15 arcminutes.

The land use data was obtained from two different sources. The maps of harvested area for soybeans and maize between 1990 and 2013, which defined the geographical distribution of the simulation units, was obtained from the dataset of patterns of land use, extensification, and intensification of Brazilian agriculture (Dias et al., 2016). The historical data on reported production and harvested area for soybeans, maize and second-season maize was obtained from the SIDRA database of the Brazilian Institute for Geography and Statistics, on a municipal scale (IBGE (Brazilian Institute of Geography and Statistics), 2018). The data for second season maize was only available after 2003, while the data for soybeans and maize (aggregated first and second season) could be obtained from 1990 to 2013.

We determined the planting and harvesting dates based on the dataset of planting windows for single and double-cropping in Brazil between 1974 and 2012 (Abrahão and Costa, 2018), which was obtained with the resolution of 1 degree (approximately 110 km at the Equator).

B.2.3 *Simulation units*

We classified the Brazilian territory in more than 80 thousand simulation units, and set up the model input based on the assumption that these units are homogeneous in terms of elevation, slope, soil properties and agricultural management. The methodology for delimitation of the simulation units was inspired by the procedures used and developed for the GEOBENE global database for bio-physical modelling (Skalský et al., 2008). The areas within the same thresholds of slope, elevation and soil texture are considered homogeneous response units (HRUs). The thresholds used for this delimitation are stated in Table B.2. The soil texture was calculated data from the SoilGrids global gridded soil database, and the R package Soil Texture Wizard (Moeys, 2012).

Table B.2: Classes of elevation, slope and soil texture used for delimitation of the homogeneous response units in this study.

Elevation classes (m)	<300
	300 - 600
	600 - 1100
	1100 - 1600
	1600 - 2100
	>2100
Slope classes (%)	<3
	3 - 6
	6 - 10
	10 - 15
	15 - 30
	30 - 50
	>50
Soil Texture	Coarse
	Medium
	Fine

After the classification of the HRUs, these units were further divided in order to delimitate the final simulation units, by using the grid from the crop calendar dataset (Abrahão and Costa, 2018), the grid from the climate dataset (Xavier, King, and Scanlon, 2016), municipal boundaries, and a land use mask. The land use mask determined which areas had either soybean or maize production at any point between 1990 and 2013, according to the cropland area maps produced by Dias et al. (2016). The simulation units in municipalities or areas with no soybean or maize production in the period between 1980 and 2013 were not included in their model simulations, and therefore the number of simulation units used in the model runs was different for each of the three crop setups - soybeans, maize, double-cropping soybeans-maize.

B.2.4 *Planting and harvesting dates*

The dataset of planting windows developed by Abrahão and Costa (2018) contains yearly initial and final planting dates for soybeans, for single and double-cropping systems. In the case of single-cropping maize, the crop calendars obtained by Sacks et al. (2010) present ranges for both the start and the end of the cropping season.

Abrahão and Costa (2018) developed a dataset of Brazilian soy planting-window yearly estimates for rainfed single and double cropping, during the period 1974–2012. To estimate the planting windows during this period, the authors took into account two important historical limitations: photoperiod and precipitation regime.

To account for changes in photoperiod limitations, the methodology for the development of this dataset considered the temporal development of soybean varieties with cycles that allowed planting in lower latitudes, as well as varieties that allowed planting a second crop. In this context, it was assumed that in each latitude band farmers would have planted the soybean crop only after, and as soon as, they had access to varieties well-adapted to their longest photoperiod dates in their latitude.

To account for limitations related to timing and duration of the rainy season, the onset and end of the agricultural rainy season was determined each year using a modified version of the Anomalous Accumulation method, previously used also by Arvor et al. (2014). In this method, the planting date windows are defined as the earliest and latest possible planting dates in which the production of one (for single cropping soybeans) or two (for double cropping soy and maize) is possible within the rainy season defined by the Anomalous Accumulation method. The dataset is a 1 degree resolution map with planting windows for single and double-cropping soybeans in Brazil for each year between 1974 and 2012. Figure B.4 shows the amount of years between 2003 and 2013 in which double-cropping was considered feasible, in the available crop calendar database. We also show the amount of years in which double-cropping happened in municipalities in the states of Mato Grosso and Paraná.

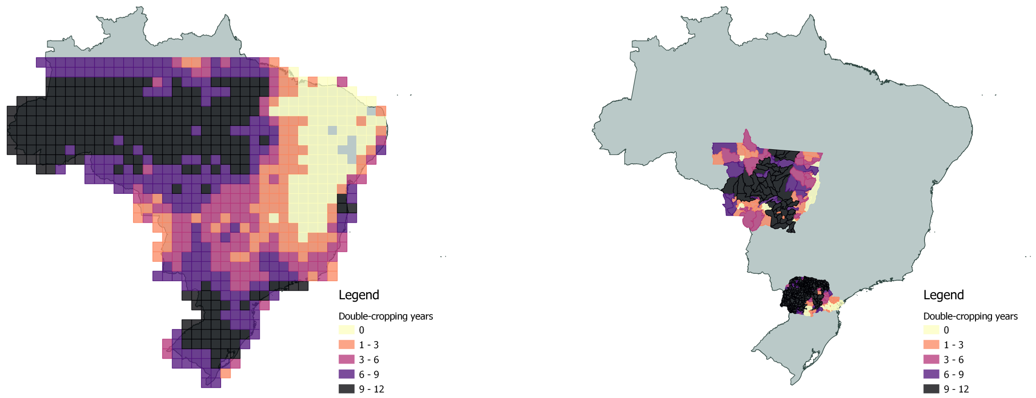


Figure B.4: Amount of years when double-cropping was considered viable between 2003 and 2013 according to the dataset of planting dates (Abrahão and Costa, 2018) (left), and the amount of years where double-cropping maize production was higher than zero per municipality in Paraná and Mato Grosso (right), according to the SIDRA database (IBGE (Brazilian Institute of Geography and Statistics), 2018).

We set up nine scenarios of planting and harvesting dates, based on these planting windows for single and double-cropping soybeans. These scenarios comprise three options for the start of the cropping season – early, mean and late planting – and three options for the length of the soybean crop cycle – short, medium and long. The early and late planting options correspond to the start and the end of the planting windows, and the mean option corresponds to the mean value between them. The short, medium and long cycles correspond to 110, 125 and 140 days. The second-season maize cycle starts one day after harvest of the soybean crop, and the length of the maize cycle corresponds to 120 days. To reduce uncertainties related to the model's sensitivity to calendar options, we selected three optimal calendar options for each simulation unit, based on the highest estimated average yield (for soybean in the case of single crop runs, or soybean plus maize in double-cropping runs). In order to isolate the effect of rainy season length and evapotranspiration on the crops, we assumed minimal levels of nutrient stress in our modelling approach, and allowed the model to implement automatic fertilization with a trigger of 20% of nutrient stress. This methodology was designed to better account for geographical variability by identifying the most appropriate range of planting and harvesting dates within the pre-defined planting windows from the input dataset.

In the case of single-cropping maize, the crop calendars obtained by Sacks et al. (2010) present ranges for both the start and the end of the cropping season. Therefore, for single-crop maize, we simulated only three scenarios options, for the start and end of the cropping season – early, mean and late planting. The final values of water demand correspond to the average of the results of these three scenarios.

B.2.5 *Potential heat units*

EPIC models the phenological development of the crop based on daily heat unit accumulation (Sharpley and Williams, 1990). Potential heat units (PHU) correspond to the total number of heat units or growing degree days needed to bring the plant from emergence to physiological maturity. We calculated the potential heat units (PHU) for each crop, simulation unit, and crop calendar scenario. The daily heat unit accumulated by the crop from planting to harvesting corresponds to the average between the daily maximum and minimum temperature minus the crop's base temperature.

$$HeatUnits = \frac{T_{Max} - T_{Min}}{2} - T_{Base} \tag{B.1}$$

The PHUs per simulation unit were defined as the average of the accumulated heat units from harvesting to planting, throughout all simulated cropping seasons, as shown in Equation B.2.

$$PotentialHeatUnits = \left(\sum_{i=1980}^{2014} \sum_{j=PlantingDate}^{HarvestingDate} HeatUnits_{i,j} \right) / 24 \tag{B.2}$$

Where i is the year, j is the day of the annual cycle, and 24 is the total amount of years between 1990 and 2013.

B.2.6 *General modelling framework*

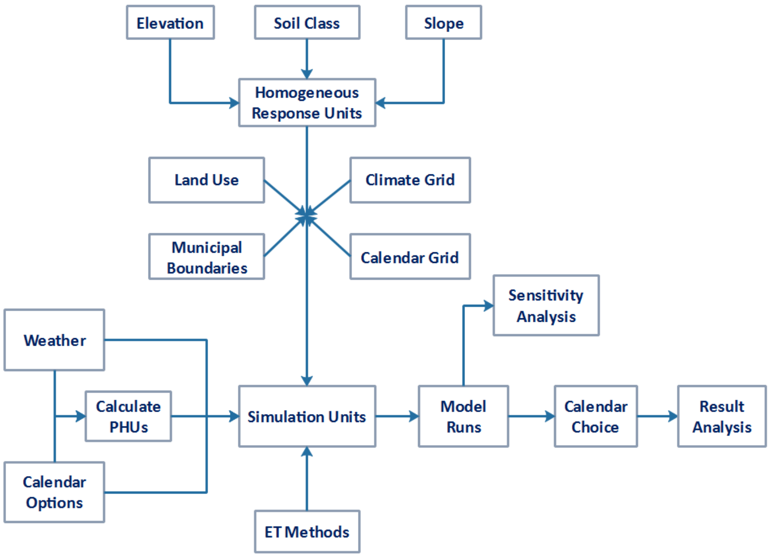


Figure B.5: Flowchart with the main steps in the modelling presented in this article.

B.3 DETAILED RESULTS

B.3.1 *Sensitivity to cropping calendar scenarios*

As the GSET is highly dependent on the cropping season, the first step in our analysis was to evaluate the distribution of GSET values for all nine calendar scenarios. Figure B.6 shows the distribution of the GSET per simulation unit for all calendar options, for single-cropping soybean, double-cropping soybean, and second season maize. Longer soybean cropping seasons result in higher total GSET for soybeans, but it is the opposite for maize. The influence of date of the start of the cropping season is higher for single-cropping than for double-cropping soybeans. The relative influence of the length and start of the cropping season is dependent on the region of the country.

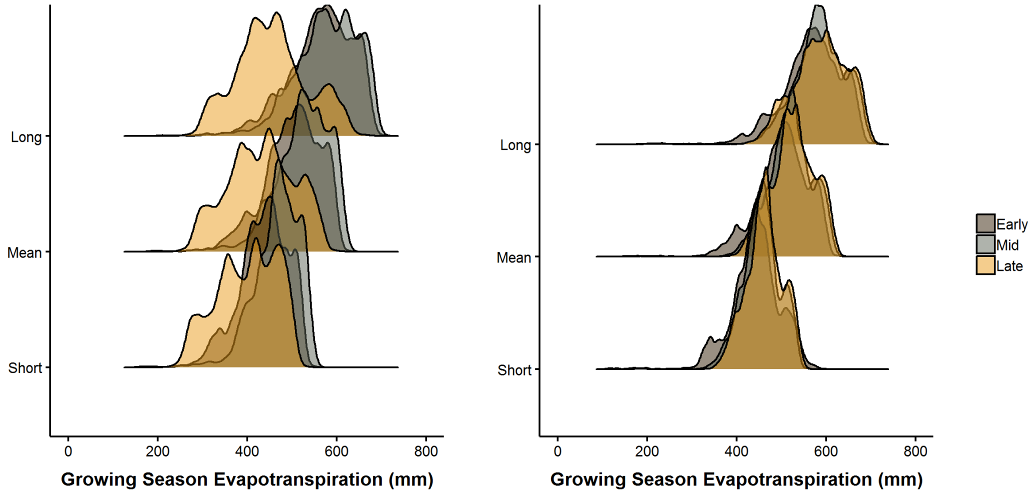


Figure B.6: Distribution of average growing season evapotranspiration (GSET, mm) by simulation unit for all crop calendar scenarios, for single-cropping soybeans (left), and double-cropping soybeans (right). For single-cropping soybeans, the values correspond to the average for all years; for double-cropping soybeans, the values correspond to the average for all years when double-cropping was considered feasible.

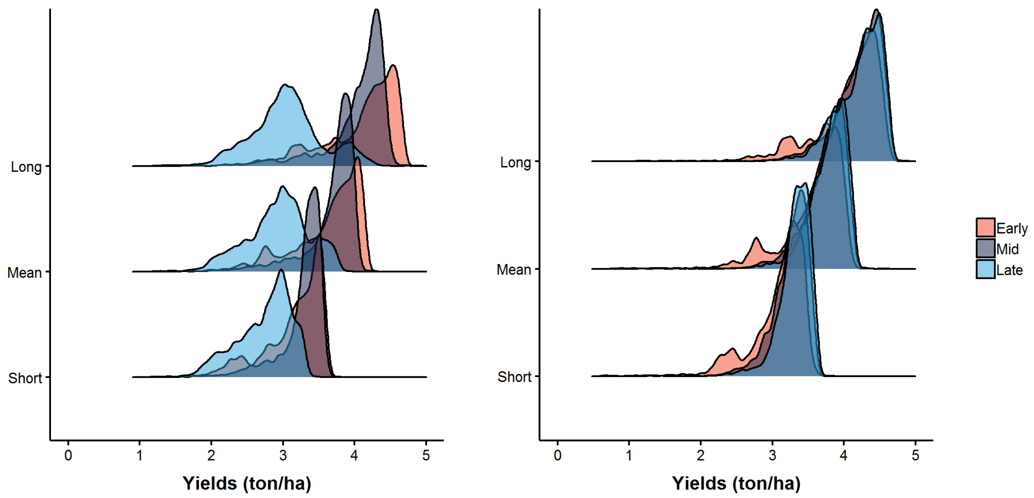


Figure B.7: Distribution of potential yields (ton/hectare) by simulation unit for all crop calendar scenarios, for single-cropping soybeans (left), and double-cropping soybeans (right). For single-cropping soybeans, the values correspond to the average for all years; for double-cropping soybeans, the values correspond to the average for all years when double-cropping was considered feasible. In the double-cropping graphs, the labels "long", "mean" and "short" refer to the lengths of the cropping season of the main crop (soybeans).

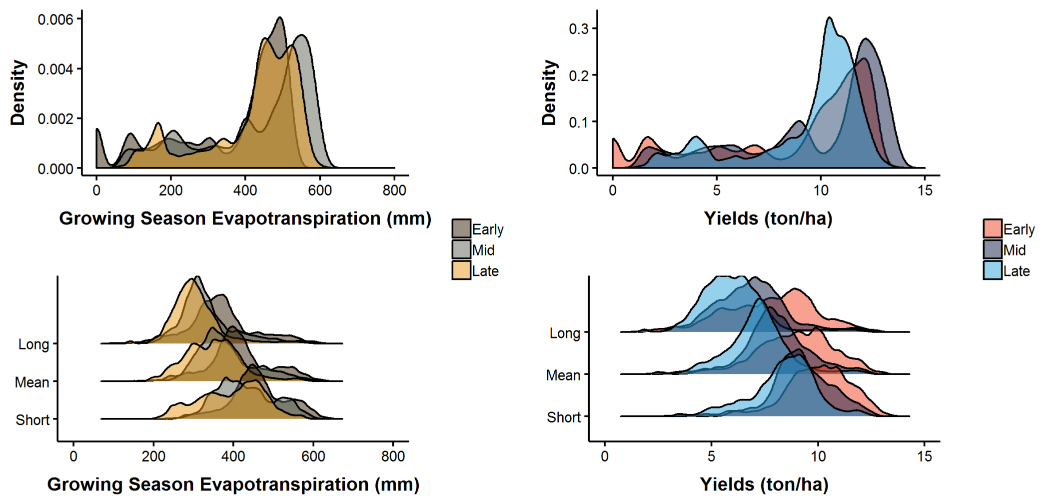


Figure B.8: Distribution of average growing season evapotranspiration (mm, left) and potential yields (right, ton/ha) by simulation unit for all crop calendar scenarios, for single-cropping maize (top), and double-cropping maize (bottom). For single-cropping maize, the crop calendar scenarios were obtained from Sacks et al. (2010), with fixed length of the cropping season. For single-cropping soybeans, the values correspond to the average for all years; for double-cropping soybeans, the values correspond to the average for all years when double-cropping was considered feasible. In the double-cropping graphs, the labels "long", "mean" and "short" refer to the lengths of the cropping season of the main crop (soybeans).

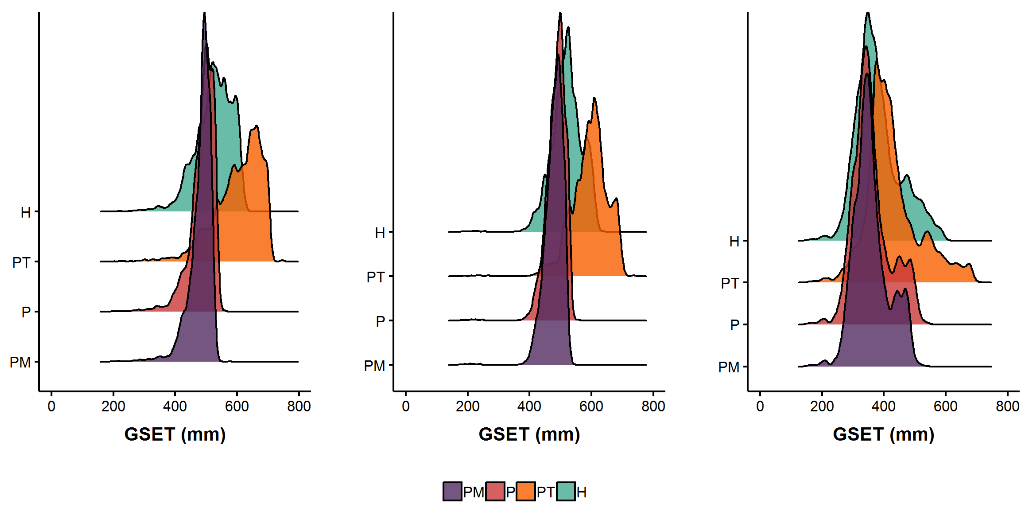


Figure B.9: Distribution of average growing season evapotranspiration (mm) by simulation unit for single-cropping soybeans (left), double-cropping soybeans (middle), and double-cropping maize (right) for 4 different methods for estimation of evapotranspiration. PM: Penman-Monteith, P: Penman, PT: Priestley-Taylor, H: Hargreaves.

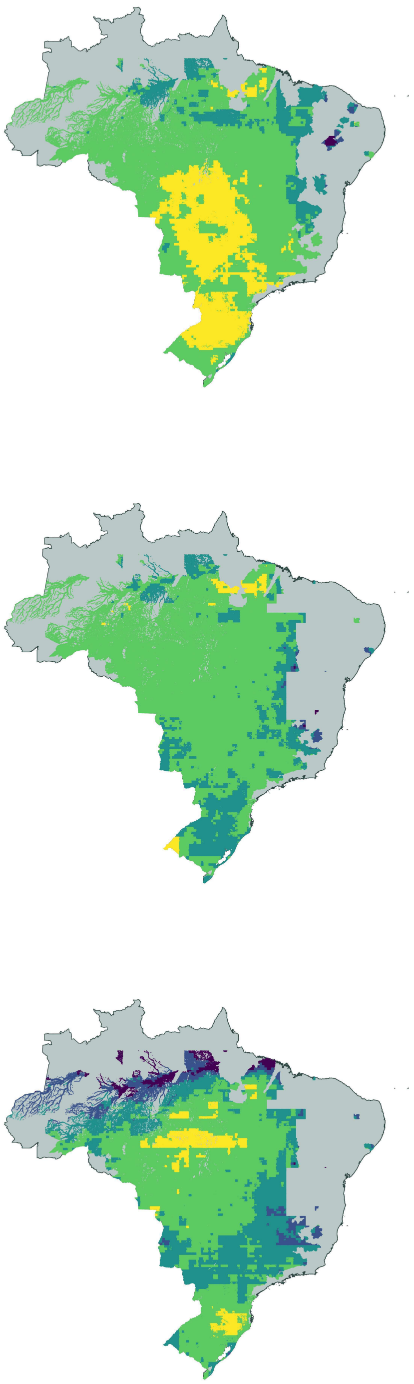


Figure B.10: Standard deviation of growing season evapotranspiration values per simulation unit across nine calendar options (left) and four potential evapotranspiration methodology options (right) for single-cropping soybeans (upper panel), double-cropping soybeans (middle panel), and double-cropping maize (bottom panel).

B.3.2 *General model simulation results*

After selecting the most viable crop calendar options for every simulation unit, it was possible to calculate the average growing season evapotranspiration for single and double-cropping options. Table B.3 shows the temporal average for all crops, aggregated for all Brazilian macro-regions (for the geographical division of Brazilian macro-regions, see Figure B.1). The values for single-cropping maize and soybeans correspond to the average for all years between 1990 and 2013, while the double-cropping values correspond to the average for all years in which double-cropping was considered feasible, both by the historical records, and the evaluation carried out by Abrahão and Costa (2018) in determining the yearly crop calendars used in this study.

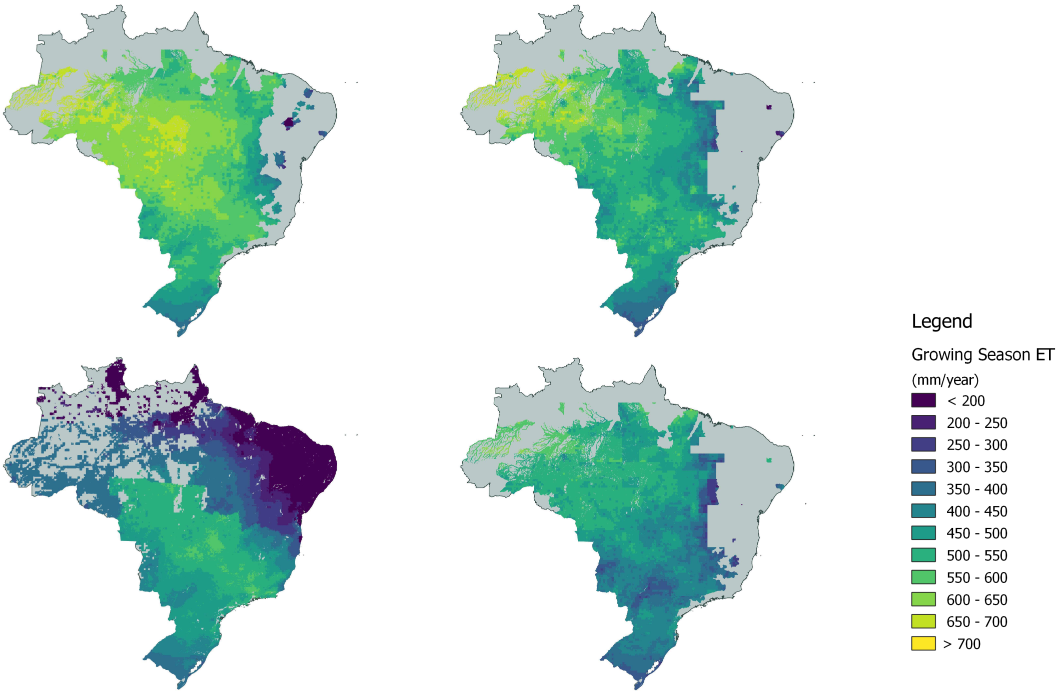
Table B.3: Average growing season evapotranspiration (mm) for single and double-cropping soybean, and second season maize for the five Brazilian macro-regions.

Region	Soybeans - single crop	Soybeans - double crop	Maize - single crop	Maize - second season
North	602.5	495.2	278.5	498.0
Northeast	535.8	277.4	154.1	244.2
Center-West	613.8	521.6	524.1	444.4
Southeast	569.2	335.2	505.1	245.9
South	505.8	505.0	469.2	379.3

The main determining factor for the differences in growing season evapotranspiration between crops and cropping systems is the start and length of the cropping season, while the temporal and geographical variability are in great part influenced by precipitation. That is why the Northeast region, which is dominated by semi-arid climate, presents evapotranspiration values are much lower in comparison with the other regions. Since the cropping season for double-cropping soybeans is in general shorter, the growing season evapotranspiration values are therefore lower. That is the case for maize as well in most regions, excluding the North and Northeast. The reason for these anomalies is the fact that the crop calendars obtained from Sacks et al. (2010) assume an abnormally short cropping season in these regions for maize. Table B.11 presents the maps with the temporal average growing season evapotranspiration for each cropping option.

It is important to highlight that the production of soybeans and maize are not evenly distributed across the different macro-regions, and therefore the producing regions with the most harvested area contain higher relative importance. As shown in Table B.1, the Center-West and the South region together are responsible for 82% and 70% of the total harvested area for soybeans and maize, respectively.

Figure B.11: Spatial distribution of average growing season evapotranspiration (mm/year) by simulation unit for single-cropping soybeans (upper left), double-cropping soybeans (upper right), single-cropping maize (bottom left), double-cropping maize (bottom right). For the single-cropping results, the values correspond to the average for all years; for double-cropping, the values correspond to the average for all years when double-cropping was considered feasible (see Figure B.4).



B.3.3 *Water footprints*

Figure B.12 to Figure B.14 refer to the results for annual crop evapotranspiration, virtual water content, and water use for the entire Brazilian territory. Figure B.15 refers to the average ratio between crop and total evapotranspiration, and refers to the national average.

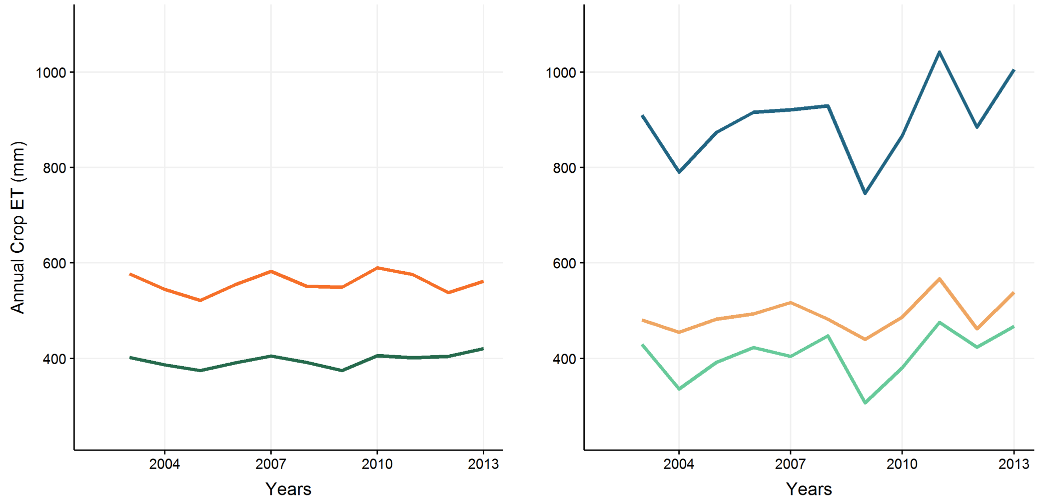


Figure B.12: Comparison of annual evapotranspiration (mm) for crops grown under single-cropping practices (left) and double-cropping (right). The annual evapotranspiration for the class "double-cropping system" equals to the sum of the evapotranspiration for the two consecutive crops.

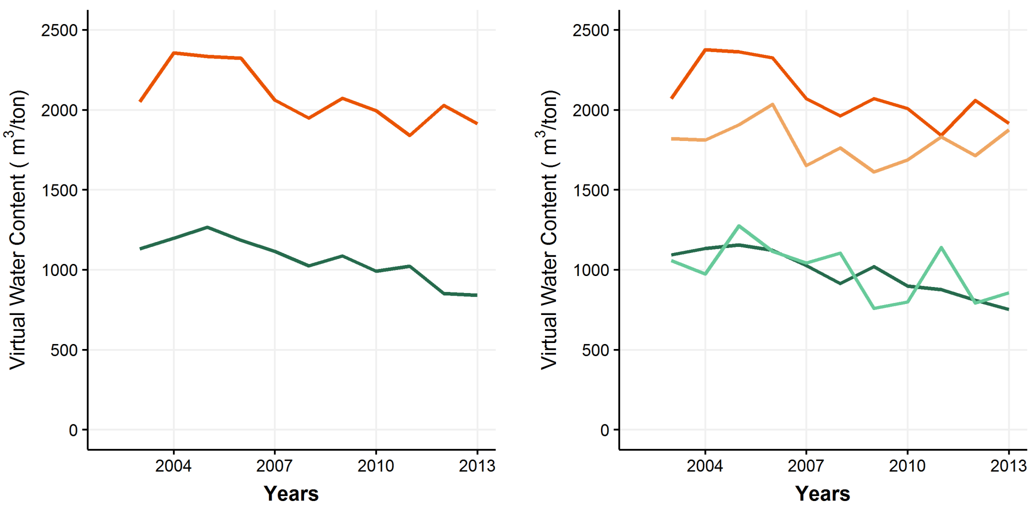


Figure B.13: Comparison of the virtual water content (m^3/ton) for crops grown under single-cropping practices (left) and double-cropping (right).

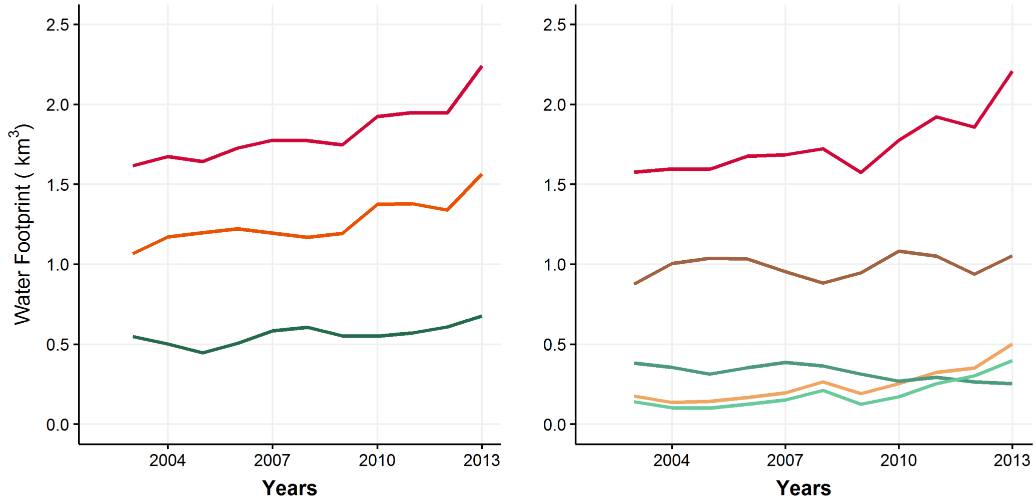


Figure B.14: Total water footprint (km^3) estimates for soybeans and maize taking into account only single-cropping conditions (left), and differentiating single and double-cropping conditions (right).

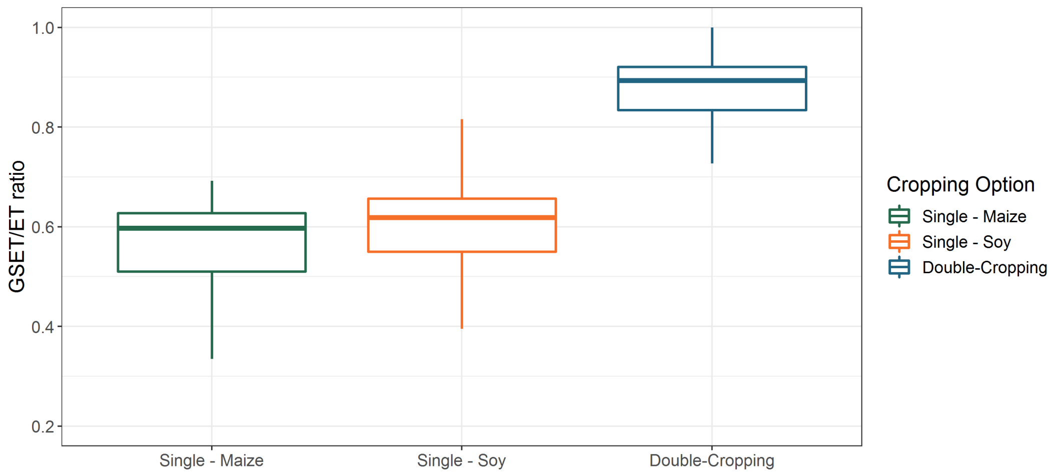


Figure B.15: Average ratio between growing season evapotranspiration (GSET, mm) and total annual evapotranspiration (ET, mm). This estimation does not consider the existence of cover crops.

BIBLIOGRAPHY

Abrahão, Gabriel M. and Marcos H. Costa (2018). "Evolution of rain and photoperiod limitations on the soybean growing season in Brazil: The rise (and possible fall) of double-cropping systems." In: *Agricultural and Forest Meteorology* 256-257.March, pp. 32–45. ISSN: 01681923. DOI: 10.1016/j.agrformet.2018.02.031.

Arvor, Damien, Vincent Dubreuil, Josyane Ronchail, Margareth Simões, and Beatriz M. Funatsu (2014). "Spatial patterns of rainfall regimes related to levels of double cropping agriculture systems in Mato Grosso (Brazil)." In: *International Journal of Climatology* 34.8, pp. 2622–2633. ISSN: 10970088. DOI: 10.1002/joc.3863.

Boer, Froukje De (2015). *HiHydroSoil: A high resolution soil map of hydraulic properties*. Tech. rep. January. Wageningen, The Netherlands: FutureWater, pp. 1–32. URL: http://www.futurewater.nl/wp-content/uploads/2015/05/HiHydroSoil-A-high-resolution-soil-map-of-hydraulic-properties.pdf.

Dias, Lívia C.P., Fernando M. Pimenta, Ana B. Santos, Marcos H. Costa, and Richard J. Ladle (2016). "Patterns of land use, extensification, and intensification of Brazilian agriculture." In: *Global change biology* 22.8, pp. 2887–2903. ISSN: 13652486. DOI: 10.1111/gcb.13314.

Hengl, Tomislav et al. (2014). "SoilGrids1km — Global Soil Information Based on Automated Mapping." In: *PLoS ONE* 9.8. Ed. by Ben Bond-Lamberty, e105992. ISSN: 1932-6203. DOI: 10.1371/journal.pone.0105992.

IBGE (Brazilian Institute of Geography and Statistics) (2018). *Levantamento Sistemático da Produção Agrícola*. URL: https://sidra.ibge.gov.br/tabela/6588 (visited on 12/13/2018).

Jarvis, A., H.I. Reuter, A. Nelson, and E. Guevara (2008). *Hole-filled SRTM for the globe Version 4, available from the CGIAR-CSI SRTM 90m Database.* Tech. rep. CGIAR. URL: http://srtm.csi.cgiar.org.

Moeys, Julien (2012). *The soil texture wizard: R functions for plotting, classifying, transforming, and exploring soil texture data*. Tech. rep., p. 36.

Philip W. Gassman, Jimmy R. Williams, Verel W. Benson, R. Cesar Izaurralde, Larry M. Hauck, C. Allan Jones, Jay D. Atwood, James R. Kiniry, and Joan D. Flowers (2004). "Historical Development and Applications of the EPIC and APEX models." In: *2004, Ottawa, Canada August 1 - 4, 2004*. St. Joseph, MI: American Society of Agricultural and Biological Engineers, p. 31. ISBN: Working Paper 05-WP 397. DOI: 10.13031/2013.17074. URL: https://lib.dr.iastate.edu/card_workingpapers/422/.

Sacks, William J., Delphine Deryng, Jonathan A. Foley, and Navin Ramankutty (2010). "Crop planting dates: An analysis of global patterns." In: *Global Ecology and Biogeography* 19.5, pp. 607–620. ISSN: 1466822X. DOI: 10.1111/j.1466-8238.2010.00551.x.

Sharpley, A.N. and J.R. Williams (1990). "EPIC: The erosion-productivity impact calculator." In: *U.S. Department of Agriculture Technical Bulletin* 1768, p. 235.

Skalský, Rastislav, Zuzana Tarasovičová, Juraj Balkovič, Erwin Schmid, Michael Fuchs, Elena Moltchanova, Georg Kindermann, and Peter Scholtz (2008). *GEO-BENE global database for bio-physical modeling v. 1.0.* Tech. rep. Laxenburg, Austria: International Institute for Applied Systems Analysis (IIASA), p. 58.

Williams, J. R., S. Dagitz, M. Margre, A. Meinardus, E. Steglich, and R. Taylor (2015). *EPIC: Environmental Policy Integrated Climate Model User's Manual Version 0810*. Tech. rep. September. Temple, Tx. URL: http://epicapex.tamu.edu/files.

Williams, J. W., R.C. Izaurralde, and E. M. Steglich (2008). *Agricultural Policy/Environmental eXtender theoretical documentation*. Tech. rep. June. Temple, Texas: Blackland Research and Extension Center, p. 131.

Xavier, Alexandre C., Carey W. King, and Bridget R. Scanlon (2016). "Daily gridded meteorological variables in Brazil (1980-2013)." In: *International Journal of Climatology* 36.6, pp. 2644–2659. ISSN: 08998418. DOI: 10.1002/joc.4518. arXiv: 1311.1716.

ACKNOWLEDGMENTS

My PhD journey was not conventional, and definitely was not an easy one. During this time I can say I learned a lot about how to become a scientist, about my field of study, about how to do independent research, and also a lot about myself. A lot of times I didn't think I would make it, and if I did, it is because I had great people around me who believed I could.

I would like to first express my gratitude to the members of my advisory committe. My supervisor Prof. Dr. Uwe Schneider, who gave me the opportunity to pursue my PhD at the Research Unit Sustainability and Global Change, in the University of Hamburg. Dr. Kerstin Jantke, who is a great inspiration to me as a scientist and a person. I greatly appreciate your time, guidance, support and advice. Prof. Dr. Julia Pongratz, who kindly accepted to be a member of my advisory panel, for her encouragement and support.

I appreciate very much the opportunity to be part of the International Max-Planck School on Earth System Modeling, and feel fortunate to be part of its environment of excellence and scientific exchange. Particularly, I would like to show my appreciation to Dr. Antje Weitz, Cornelia Kampmann the IMPRS-ESM office team, for their warm and friendly support in helping me navigate life and work in Hamburg.

This thesis would definitely not be the same without my co-authors, with whom I had the immense pleasure to collaborate. They provided me with invaluable feedback, exchange of ideas, and development of new ways of looking at the my research.

My sincere appreciation to my PhD colleagues at the Research Unit Sustainability and Global Change and the International Max Planck School on Earth System Modeling, for the camaraderie and shared experiences.

I am very lucky for the friends I made in Hamburg, who made my life in this city very special. I will always have a ton of appreciation and admiration for my friends and bouldering partners Sally, Sebastian Milinski, and Sebastian Mueller. While convincing me that I could work harder and do better climbing, you also showed me how strong I can be when I stop doubting myself too much. I am grateful to Katherine, who give me shelter and support in some of the moments when I needed the most. I feel lucky to have had Elnaz's support and friendship, which I will always cherish. Big thank you to Friederike for all the fun moments, and for being an inspiration on what I want to be when I am "on the other side" of the PhD journey. To Philipp, thanks for kindly accepting my last minute request for a German translation of this thesis' abstract.

My infinite gratitude to my parents, who always have my back, and have always been my greatest cheerleaders.

VERSICHERUNG AN EIDES STATT

Declaration of oath

Hiermit versichere ich an Eides statt, dass ich die vorliegende Dissertation mit dem Titel: On the interactions between land and water use in Brazilian rainfed agriculture – selbstständig verfasst und keine anderen als die angegebenen Hilfsmittel – insbesondere keine im Quellenverzeichnis nicht benannten Internet-Quellen – benutzt habe. Alle Stellen, die wörtlich oder sinngemäß aus Veröffentlichungen entnommen wurden, sind als solche kenntlich gemacht. Ich versichere weiterhin, dass ich die Dissertation oder Teile davon vorher weder im In- noch im Ausland in einem anderen Prüfungsverfahren eingereicht habe und die eingereichte schriftliche Fassung der auf dem elektronischen Speichermedium entspricht.

Hamburg, den 17.06.2020

Rafaela Ariana Flach

Hinweis / Reference

Die gesamten Veröffentlichungen in der Publikationsreihe des MPI-M
„Berichte zur Erdsystemforschung / Reports on Earth System Science“,
ISSN 1614-1199

sind über die Internetseiten des Max-Planck-Instituts für Meteorologie erhältlich:
http://www.mpimet.mpg.de/wissenschaft/publikationen.html

All the publications in the series of the MPI -M
„Berichte zur Erdsystemforschung / Reports on Earth System Science“,
ISSN 1614-1199

are available on the website of the Max Planck Institute for Meteorology:
http://www.mpimet.mpg.de/wissenschaft/publikationen.html