Student thesis series INES nr 333

Present and near future water availability for closing yield gaps in four crops in South America

Karla Markley

2015
Department of Physical Geography and Ecosystems Science
Lund University
Sölvegatan 12
S-223 62 Lund
Sweden

Karla Markley (2015) Present and near future water availability for closing yield gaps in four crops in South America

Master degree thesis, 30 credits in Physical Geography and Ecosystems Analysis

Department of Physical Geography and Ecosystems Science, Lund University

Level: Master of Science (MSc)

Course duration: September 2014 to January 2015

Disclaimer

This document describes work undertaken as part of a program of study at the University of Lund. All views and opinions expressed herein remain the sole responsibility of the author, and do not necessarily represent those of the institute.

Present and near future water availability for closing yield gaps in four crops in South America

---

Karla Susana Markley Vergara

Master thesis, 30 credits,

in Physical Geography and Ecosystem Analysis

Supervisor: Per Bodin

Examiner 1: Ben Smith

Examiner 2: Yengoh Genesis Tambang

Department of Physical Geography and Ecosystem Science

Lund University

Table of contents

List of Figures

Appendix figures

Acknowledgments

I would like to thank to my supervisor Per Bodin, who has supported and guided me during the development of this work. I also thank to Stefan Olin, who has shared with me important information to fulfill this study.

I express my thanks to all teachers, researchers and administrative staff related in one way or the other to this study and to my attendance during these two years in Lund University.

I want also to express my gratitude to my fellow students and friends that have shared beautiful moments with me during this master program.

And finally, I want to thank to my beloved family, especially to my parents and daughter, for all their unconditional support during this very important period in my life.

Abstract

Sustaining crop yields present challenges worldwide. These challenges vary regionally and climate change may have positive or negative effects on crop yields. Closing yield gaps in already established cropping areas is one of the solutions to increase future food supply. Fraction water yield gaps are defined as how far yields with high levels of nutrients are from attainable (irrigated) yields. In this study the largest water yield gaps for maize, rice, wheat and potato in South America are located. Climate change over a fifty-year period influences these water gaps generating large positive or negative changes for maize, wheat and potato mainly in Paraguay, Uruguay and Argentina. South America presents a great potential to increase yields by irrigation for the four crops in this study. Looking also at available water during the growing period it is possible to identify regions of large suitability to increase yield. Suitability further changes over time display negative or positive trends for few areas reflecting future changes in climate and yield.

Keywords: fraction water yield gap, water yield gap, growing season precipitation, LPJ-GUESS, Climate change

1. Introduction

1.1. Problem definition

Future decades will bring several challenges related to food security, water management and environmental sustainability. With a population expected to surpass 9 billion people by 2050 (United Nations, 2009), and a crop demand that will increase between 100 and 110% from 2005 to 2050 (Tilman et al., 2011), it is imperative to find alternatives to increase crop yields while diminishing stress on the environment.

Mueller et al. (2012) have found that yield variability is heavily controlled by fertilizer use, irrigation and climate. Water scarcity is the main factor that limits crop yield in some zones; and even some irrigated areas can face this problem and its yields are therefore affected (FAO, 2012). Crop yields can be maximized by closing yield gaps, and according to Mueller et al. (2012) reaching 100% of attainable yields will give an increase in production from 45 to 70% for most crops.

Availability of freshwater is crucial for human consumption, agricultural activities, energy projects, ecological cycles, and it is under increasing pressure due to changes in temperature and precipitation patterns and higher human demands. In South America, the agricultural sector is the main water consumer (Magrin et al., 2007). Therefore, water for irrigation is a major concern in the context of climate change and its impacts will suppose important investment in this area (Elliott et al., 2014).

Another important concern is the threat that agricultural expansion means to several ecosystems around the world. In South America, for instance, much of the remaining cultivable land is under the tropical rain forest (Licker et al., 2010). Even though under climate change projections South America would have a surplus of water supply (Elliott et al., 2014), it is necessary to understand how this will influence water yield gaps. These gaps are defined as the difference between observed yields (in this case water-limited yields) and those attainable in a given region (Mueller et al., 2012; van Ittersum et al., 2012). There might be regions where precipitation patterns can offer a possibility to increase yield and others in which it is a limiting factor.

Four crops have been selected for this investigation: maize, rice, wheat and potato. In terms of grain production, maize is the most important crop in the world, while wheat and rice are the most important for direct human consumption. Rice also signifies the nutriment of 3 billion people worldwide. Wheat is the third largest crop in the world and potato ranks as the fourth, with a production of 329 million tonne on 18.6 million ha[1] (FAO, 2012).

1.2. Aim and objectives

The aim of this study is to provide information about water availability, water yield gaps and most suitable areas to close these gaps in South America. Two different time horizons will be analyzed: present (2000 for the global yield datasets and 2001-2010 decadal mean for model output) and future (2041-2050 decadal mean), for four different crops: maize, wheat, rice and potato. To achieve this aim several questions have been established:

1.2.1. What are the actual (based on observed data) and near future (based on observed and simulated data) water gaps for South America?

1.2.2. How will these water gaps change in the future in relation to climate change?

1.2.3. Which are the most suitable areas for present and near future to close water yield gaps for maize, wheat, rice and potato?

2. Conceptual framework

2.1. Brief technical terms review.

Crop yield is defined as the amount of harvested product per area of the crop (Fermom and Benson, 2011). Yield gaps are differences between observed yields and those attainable in a given region (Mueller et al., 2012). Factors that contribute to yield gaps can be biophysical: nutrient deficiencies and imbalances, water stress, flooding, suboptimal planting, soil problems, weed pressures, insect damage, diseases, lodging and inferior seed quality; or socioeconomic:

[1] In this paper yield is expressed as kg/m^2. The relationship is 1 ton/ha = 0.1 kg/m^2

risk aversion, inability to secure credit, limited time devoted to activities, lack of knowledge on best practices (Lobell et al., 2009).

Fraction yield gap gives information about how close to potential yield any location may be. A value of 0 or close to it means that the area is near to the potential yield. On the contrary, a value of 1 stands for an area that is very far from the attainable yield (Licker et al., 2010).

Potential yield (Yp) for the four crops has been determined by identifying high yield areas with no limitation of water or nutrients for them, and in which any biotic stress has been controlled. These areas have a same climate and any difference in crop grown is driven by factors as solar radiation, temperature, atmospheric CO_2 and genetics (van Ittersum et al., 2012). This study is focussed on water limited yield (water yield gap), as it is calculated based on rainfed yield, potential yield and irrigated yield, respectively. Water yield gap (Yw) is similar to potential yield but in this case water is also a limiting factor (van Ittersum et al., 2012).

2.2. Maize, wheat, rice and potato general characteristics.

With vast areas of land, a range of reasonable climates and low cost, South America is one of the main food producers and exporters in the planet, but its agriculture sector is very vulnerable due to market and climate uncertainties (Ortiz, R., 2012). The region holds the largest potential for agricultural expansion on the one hand, and on the other hand, it is the owner of the biggest tropical forest on the planet (Magrin et al., 2014). In terms of deforestation and land degradation, extensive and intensive agriculture, are the main drivers (Magrin et al., 2014).

Maize crop, *Zea mays,* is a species that includes hybrid and ordinary maize with widely different yields in the world, and is the third largest crop in terms of extension (Leff et al., 2004). This crop presents a less intense cultivation in South America in comparison with the maize belt in U.S.A, northeastern China, Rift Valley in Africa and Eastern Europe (Leff et al., 2004). South America (Brazil, Argentina and Bolivia) produces 119.77 million of metric tonnes out of the 868 that are produced in the world; this represents 13.8% of the global maize production (USDA, 2015). In the region, maize is grown from Argentina to Venezuela along many temperature zones (Seo and Mendelsohn, 2008), but is rivalled by soybeans for dominance in the north part of the subcontinent. Along the Andes Mountains and the Brazil highlands, maize is the major dominant crop, whereas in the soybean area, from Mato Grosso to Cordoba state, and in the Chilean wheat belt, it is the second crop (Leff et al., 2004).

Maize accounts for about one third of the calorie intake in South America and has a broad variety of uses: human direct consumption, food for livestock, production of alcohol, syrup, sweetener of soft drinks, ethanol production, among others (Global crop diversity trust, n.d.). Maize production in the northern part of the region is mainly related to traditional varieties and is addressed for human consumption and animal feeding; whereas for Argentina, Chile and south Brazil, maize presents large scale production with commercial purposes (Morris and López-pereira, 2000). The two main producers by volume of grain in South America are Brazil and Argentina, with 66 and 23% of the total production of the region, respectively. The largest maize yields for South America are reported for Chile (0.85 kg/m^2) and Argentina (0.44 kg/m^2) for year 1998 (Morris and López-pereira, 2000; Núñez, 2013).

Wheat crop comprises two species, *Triticum aestivum* and *Triticum turgidum durum*, and presents a global average yield of 3 ton/ha (0.3 kg/m^2) (FAO, 2012). This crop is the most abundant in terms of cultivated area globally, representing 22% out of the total (Leff et al., 2004). Wheat is a very well spread crop, and it is grown from the arctic to the tropical highlands and from sea level up to 4500 masl (FAO, 2012). Wheat is the most important crop by aerial extent in the southern parts of South America, and is the main cultivation in La Plata region in Argentina and western coastal plain in Chile (Leff et al., 2004).

In South America the two main wheat producers are Argentina and Brazil, with a production for 2012 of 8.2 and 4.4 millions of tonnes, respectively (FAO, 2014a). This represents only 2% of the global production that attained 658.04 million of metric tonnes for the year 2013 (USDA, 2015). In general, all countries in South America are wheat importers (FAO, n.d.a), but Brazil is one of the most important in the world (5.5% of global imports) and has an interesting commercial relationship with Argentina, which is a net exporter (Universidad Austral, n.d.). For year 2004, Argentina represented 2.7% of worldwide wheat production (Zucchini, n.d.).

Oryza sativa and *Oryza glaberrima* are the two species representing cultivated rice worldwide. The latter is grown in parts of West Africa. *Oryza sativa* has two races: *indica*, farmed in the tropics, and *japonica*, cultivated in temperate regions and highlands (FAO, 2012). Rice crop occupies tropical and subtropical belts and represents 11% of the total cultivated area in the world, being the second most extensive crop (Leff et al., 2004). Rice has two main environments to grow in: lowland, with saturated soils and ponded water, and upland, with well drained soils and no ponded water (FAO, 2012). In South America, rice accompanies maize along the Andes belt, in the west lowlands of Colombia and Ecuador. Other zones of rice cultivation are the northern coastlines and Tocantins river basin (Leff et al., 2004).

Rice is a staple food crop for people in South America and the second most important source of daily calories (Ricepedia, n.d.). This crop is also an important source of employment, food, energy and income for poor smallholders in the region (CIAT, 2013; FAO, n.d.b). Per capita annual consumption in Latin America and the Caribbean has increased from 10 to 30 kg between 1924 and 2010 (Ricepedia, n.d.; FAO, n.d.b). Out of 1 million farmers producing rice in the region, 0.8 million are smallholders and produce 6% of the total cultivar, while the other 0.2 million are mechanized producers that bring out the remaining 94% (Ricepedia, n.d.). Brazil, Peru and Colombia are the main rice producers for year 2009 with 12.65, 2.99 and 2.98 millions of tonnes respectively (CIAT, 2013). This production represents 4% of the total world production that reached 471.88 million of metric tonnes for the year 2013 (USDA, 2015).

Potato is represented by two subspecies, *Solanum tuberosum tuberosum* (cultivated in Venezuela, Chile, Argentina, Uruguay, Paraguay, Brazil and Bolivia) and *Solanum tuberosum andigena* (cultivated in Colombia, Ecuador, Peru and Bolivia). It is a tuberous crop originated and domesticated in the Andes (FAO, 2012; CIP, 1999); nevertheless this same region presents the lowest production level worldwide. Potato is a staple food crop as maize, rice and wheat, wide spread in the entire world and adapted to most agro-ecological zones (FAO 2008; CIP, 1999; CIP, n.d.; Kiple and Connè Ornelas, 2000).

In South America, the cultivation of potato is concentrated in the mountains of Chile and Colombia (Seo and Mendelsohn, 2008) and complements the maize Andean belt along Peru and

Bolivia (Leff et al., 2004). Potato produces more food per unit of water than any other major cultivar and can reach water usage efficiency seven times higher than cereals (CIP, n.d.). Highest yields in the region are produced by Argentina with 2.87 kg/m^2, Brazil with 2.37 kg/m^2 and Colombia with 1.73 kg/m^2 (FAO, 2008). For year 2007, South America produced 13.34 million of metric tonnes representing 4% of the world production for the same year achieved (325.30 million of metric tonnes) (FAO, 2008). Figure 1 shows the actual[2] yield for the fours crops on the region.

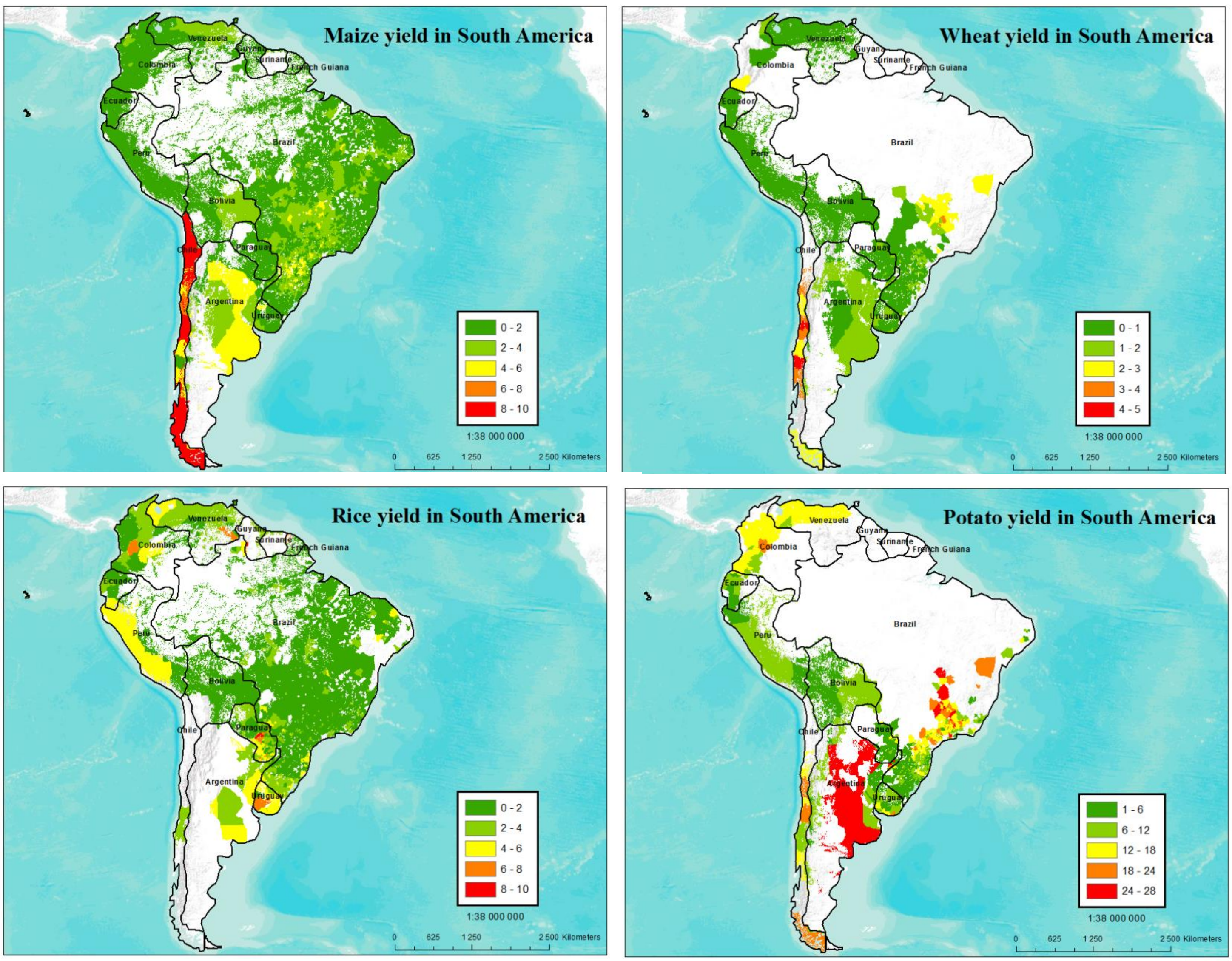


Figure1. Yields for maize, whear, rice and potato crops in South America for year 2000. Units in ton/ha. Modified from Monfreda et al., 2008.

[2] Actual yield is the yield actually observed in a given location, which may be significantly different than the climatic potential yield (Licker et al., 2010).

2.3. Growing season and precipitation trends in South America.

South American precipitation patterns for last decades of 20th century have shown decreasing trends for Chilean central-south, southwest Argentina and southern Peru (Magrin et al., 2007). There is also a clear increasing trend for annual rainfall for northwest Peru and Ecuador and southeastern part of the South America (Magrin et al., 2007).

The observed increasing precipitation in Peru and Ecuador has led to an increase in the occurrence of landslides and flash floods (Magrin et al., 2007); and a potential increase in future climate variability will lead to stronger and more frequent extreme events, and a reduction in some crop yields (Rowhani et al., 2011). Wetter conditions can also bring benefits for summer crops and pasture productivity, and may facilitate agricultural expansion (Magrin et al., 2014). Land use change due to agricultural expansion along with precipitation increments, has affected fragile ecosystems, mainly in edges of Amazon forest and tropical Andes (Magrin et al., 2014).

Growing season is defined as “the period of time when temperature and moisture conditions are suitable for crop growth”, and it is determined by the beginning of the rainy season, potential evapotraspiration and temperature (HarvestChoice, 2010). A normal growing period is composed by three stages: i) dry period, in which precipitation equals the half of potential evapotranspiration (ET); ii) moist period, in which precipitation equals the potential evapotranspiration; and iii) and wet period, in which ET is exceeded by precipitation (FAO, 2014b). Growing season precipitation (GSP) in this study is defined as the total amount of precipitation in a region over the actual growing season (between sowing and harvest).

Temperature and precipitation changes during growing season have slowed positive yield trends in crops as soy, maize and wheat in South America (Magrin et al., 2014). According to Xia et al. (2012) and Porter et al. (2014) global warming has an enlargement effect on growing seasons in mid-high latitudes. In general, a lengthening of 10-20 days has been reported, basically due to an early onset of this period (Xia et al., 2012). However, for tropical regions a decline in the length of growing season is likely to happen, mainly due to extreme heat and moisture availability (Jones and Thornton, 2009; Zhang and Cai, 2011).

2.4. Model, GCMs and RCP background.

Lund-Potsdam-Jena General Ecosystem Simulator with Managed Land -LPJ-GUESS is a global dynamic vegetation model (Smith et al., 2001) This model was extended to include also crops (Lindeskog et al., 2013), building on the LPJmL model (Bondeau et al. 2007) and a new sowing algorithm (Waha et al., 2012). LPJ-GUESS and LPJmL represent biophysical and biogeochemical processes along with productivity and yield for most important crops in the world, using the concept of crop functional types (Bondeau et al., 2007). Sowing dates are calculated based on temperature and precipitation and harvest dates are simulated by the model using a temperature sum approach. A new feature in LPJ-GUESS is the inclusion of land abandonment and afforestation, where cropland and pasture can be introduced to former forested land and vice versa (Lindeskog et al., 2013). The model simulates full carbon and water cycles at a daily time step, and as crop growth is only driven by climate simulated yield can be said to represent potential yield. The version of LPJ-GUESS used in this study does not include the representation of nitrogen stress (Rosenzweig et al., 2014). Recent developments include the full representation of the nitrogen cycle for both natural vegetation (Smith et al., 2014) and croplands (Olin et al., accepted).

Atmosphere-Ocean general circulation models –AOGCMs represent the dynamics of the atmosphere, ocean, land and sea ice as physical components of the climate system. AOGCMs allow us to make future projections according to greenhouse gases and aerosol forcing (Flato et al., 2013). Model results from five AOGCMs were used as model input to the LPJ-GUESS model in this study: HADGEM2-ES, GFDL-ESM2M, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1-M (Flato et al., 2013).

The above AOGCMs have been run under several representative concentration pathways (RCPs). Here, the GCM for only one RCP (RCP 8.5) was used. RCPs are scenarios that lead to total radiative forcing (RF) at the end of 21st century developed using different combinations of economic, institutional, technological, demographic and political futures (Cubasch et al., 2013). There are four RCPs recognized by the 2100 peak or stabilization value of the RF, relative to pre-industrial levels. The lowest, RCP2.6, peaks at 3.0 Wm^{-2} and then declines to 2.6 Wm^{-2} in 2100; the low-medium scenario, RCP4.5, stabilizes after 2100 at 4.2 Wm^{-2}. RCP6.0, medium-high, stabilizes after 2100 at 6.0 Wm^{-2}; while the highest RCP, 8.5, reaches 8.5 Wm^{-2} in 2100 and continue to increase after this year (Collins et al., 2013).

RCP8.5 is considered a non-climate policy scenario because it is a high baseline emission scenario (Riahi et al., 2011). It was developed by the International Institute for Applied Systems Analysis (IIASA), based on MESSAGE model and the Integrated Assessment Framework (Vuuren et al., 2011). Future assumptions of this RCP include: high population growth and therefore, is an energy intense scenario. It is also characterized by a slow income growth in developing countries and a moderate technological improvement. In terms of land use change, croplands and grasslands area increases, while vegetation area decreases as a consecuence of population growth (Riahi et al., 2011). RCP8.5 is considered to be the bussiness as usual scenario and is often used for future impact studies assuming no climate mitigation. This was also the RCP used in the study form where the simulated yield in this study ewre taken (Rosenzweig et al., 2014). Further, for near future climate the difference between RCPs is relatively small.

SRES (Special Report on Emmision Scenario) A2 radiative forcing is comparable to RCP8.5, but the latter is higher during the 21st century due to a faster decline in radiative effect of aerosols in RCP8.5 (Collins et al., 2013). Some of the potential impacts under RCP8.5 include: mean surface temperature increase for 2081-2100 between 2.6º and 4.8 º (Collins et al., 2013), reductions in Arctic sea extent in the same period of 34% for February and 94% for September (Collins et al., 2013), a near-surface permafrost area decrease of 81%, etc. (Collins et al., 2013).

3. Methodology

3.1. Present changes in water yield gaps

Two different sets of data were used to calculate the fraction water yield gap and the water yield gap for the current period of time. Potential yield was taken from Monfreda et al. (2008), available at http://www.earthstat.org/ web page. Values for rainfed high yield were taken from You et all. (2010), available at http://mapspam.info/data/ web page.

The data for potential yield shows climate-defined potential yield in comparison with other yields in an area of the same climate for the year 2000, calculated as the 95th percentile value of all current yields in a climate space (Monfreda et al., 2008). It was obtained in ASCII format with a spatial resolution of 5 x 5 minutes at the equator. The spatial reference system for the data was GCS_WGS_1984, with a cell size of 0.083333 degrees (Monfreda et al., 2008). Using the conversion tool in ArcGis, the resolution of the data was transformed into 0.5 x 0.5 degrees.

Rainfed high system is defined as "rainfed-based agriculture that uses high-yield varieties and some animal traction and mechanization. It at least applies some fertilizer, chemical pest, disease or weed controls" (You et all., 2010). Data was obtained as .dbf tables with a resolution of 0.5 x 0.5 degrees for year 2000 with spatial reference system GCS_WGS_1984.

Present fraction water yield gap (fYw) and water yield gap (Yw) were calculated based on potential yield and yield for rainfed high system. fYw is a value from 0 to 1 that let us know how close to the potential yield any location could be.

All the data layers used in this study were transformed from WGS84 geographic coordinate system to Albers Equal Area Conics projected coordinate system. This map projection is one of the best for South America as it preserves area and has a suitable extent for the zone as a subcontinent (Hunter College of the City University of New York, n.d.). This projection transformation was done applying the project raster tool with a nearest resampling technique. All resulting maps are therefore projected with a resolution of 58927 x 58927 meters.

Fraction Yw was calculated as follows (Deryng et al., 2011), applying raster calculator spatial analysis tool in ArcMap:

$$\text{fYw} = 1 - \frac{\text{Y rainfed high}}{\text{Y potential}} \qquad (1)$$

Yw for the four crops was calculated according to the following formula (Licker et al., 2010):

$$Yw = Y\ \text{potential} - Y\ \text{rainfed high} \quad (2)$$

In cases where Yp<Yrh or if Yp=0 the grid cells were excluded from the analysis (0.5≤ % of all grid cells for any of the crops).

3.2. Near future changes in water yield gaps

The absolute difference between future (2041-2050) and present (2001-2010) decadal mean simulated yield was calculated for both rainfed and irrigated crops. The calculations were made using the mean of 5 simulations made with the LPJ-GUESS model, using climate input from 5 GCMs, taken from Rosenzweig et al. (2014). Future values for Yp and Yrh were calculated by adding the absolute change in simulated yield as calculated above to the values taken from the observational datasets, assuming that simulated irrigated yields are equivalent to potential yields in observed data. Using these values for future Yp and Yrh, future fYw and Yw were calculated using formula 1 and 2. Model outputs were obtained as excel files with a resolution of 0.5 x 0.5 degrees.

3.3. Water yield gap and growing season precipitation relative change

The relative change (in %) in fYg and GSP (LPJ-GUESS model output) were calculated using present and future fYw and GSP layers (in appendix) and applying the following formula (Mast and Pawlak, n.d.) by using the raster calculator tool:

$$\text{relative difference} = \frac{\text{final value} - \text{initial value}}{\text{initial value}} \times 100 \quad (3)$$

3.4. Suitable zones for closing water gaps in South America

Suitability was classified based on both the size of the fraction water gap (fYw) (potential to close the water gap by adding irrigated water) as well as the amount of available water for irrigation use during the growing period (GSP). Levels for both of these two variables were divided into low, medium or high values. This was done by first creating 5 categories for each crop and variable using natural breaks classification method in ArcGis (grouping method that best group similar values, maximizing the difference between classes). For GSP the top end of the range for the lowest two categories was forced to equal the minimum water requirements for that crop FAO (2013) and Hundertmark and Facon (n.d.). A value was considered to be low if it belonged to the lowest two categories, high to the highest two, and medium if it belonged to category 3.

The overall suitability was then assessed based on the levels on both fYw and GSP, so that if either one of these were classified as low the grid cell was classified as unsuitable for closing the fraction water gap (Table 1). If both values were at least classified as medium then said region was classified as suitable.

Table1. Suitability classification according to fYw and GSP

Level of fYw	Level of GSP	Suitability
Low	Low	not suitable
	Medium	not suitable
	High	not suitable
Medium	Low	not suitable
	Medium	suitable
	High	suitable
High	Low	not suitable
	Medium	suitable
	High	suitable

3.5. Suitability change

Using the raster calculator tool, present suitability (giving the value of 1 to suitable and 0 to not suitable) was subtracted from future suitability to generate four maps, one for each crop. These maps show the direction of the change over time in relation to suitability, as positive (from not suitable to suitable) or negative (from suitable to not suitable) changes.

4. Results

4.1. Maize crop analysis for South America

4.1.1. Current and near future water yield gaps

The areas with the largest potential to improve yield for maize in relative terms in South America are presented in orange and red colors (figure 2). These zones are situated along the Andes from Venezuela to Argentina, the central part of Chile, and the zone related to Uruguay, Paraguay and the central east part of Brazil (Tocantins). There is also a belt along Argentina that involves Viedma, Bahía Blanca, Las Pampas, Córdoba northwards to Paraguay (figure 2). These areas present a fYw that ranges from 55 to 100%. For these regions the largest potential to close the water yield gap in absolute terms (with values up to 1.33 kg/m2) can be found in southern Paraguay, central eastern and southern Brazil, along the Andes, central Argentina, and southern Uruguay (figure 3).

For the fractional water gap (figure 2, 4) and water gap (figure 3, 5) a relatively similar picture emerges for future compare to current climate. The relative change in fYw however varies across the continent with the highest difference found in Paraguay, Argentina and Uruguay. Changes up to 100% can be found in southern Paraguay and some zones in central east Argentina, with negative changes of the same order of magnitude found in southern Brazil (Figure 6).

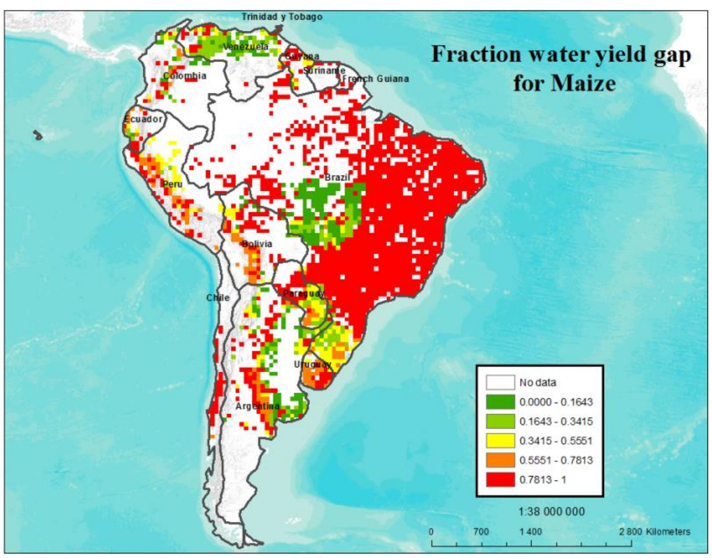


Figure2. Fraction water yield gap for maize crop for year 2000 in South America.

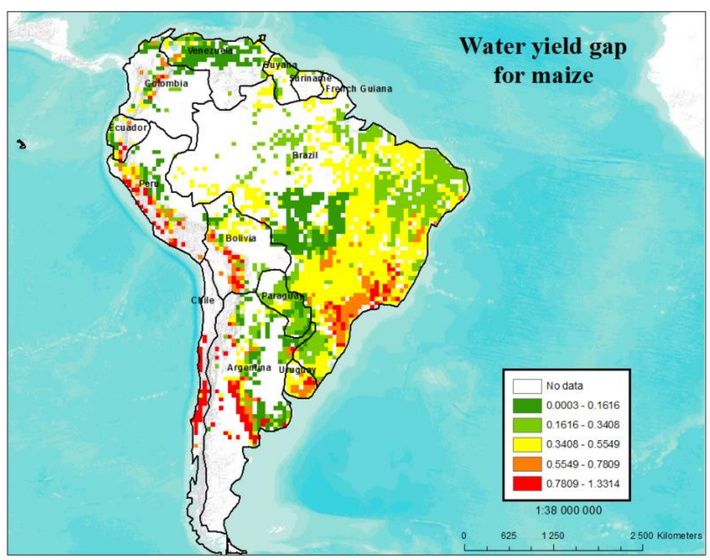


Figure3. Water yield gap for maize crop for year 2000 in South America. Units is kg/m^2

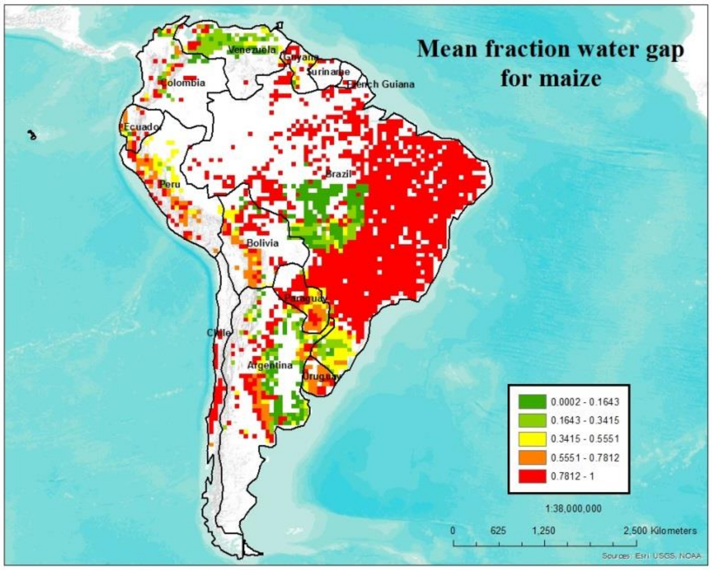


Figure4. Mean fraction water yield gap for maize crop for year 2050 in South America.

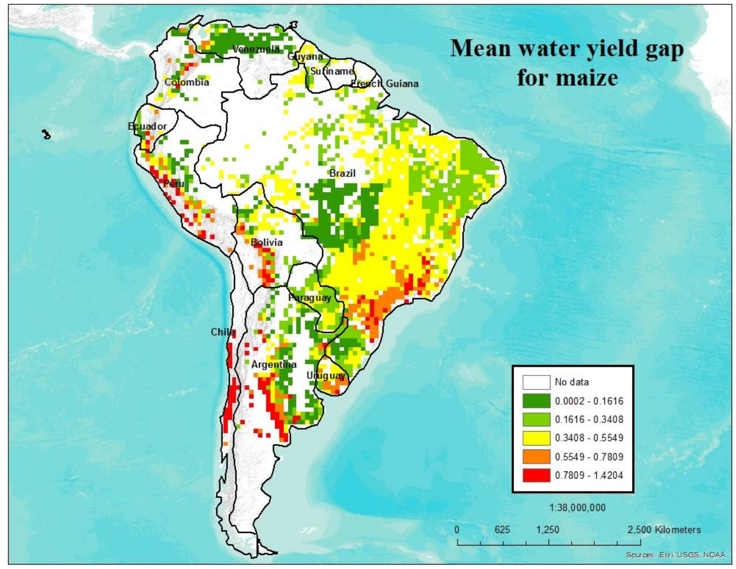


Figure5. Mean water yield gap for maize crop for year 2050 in South America. Units in kg/m^2

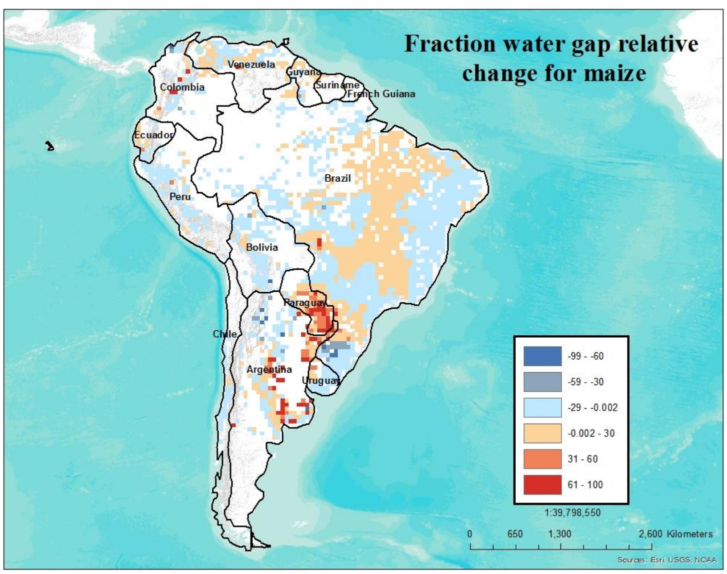


Figure6. Mean water gap relative change 2001-2050 for maize crop in South America. Units in %.

4.1.2. Growing season precipitation relative change

GSP displays positive and negative changes ranging mainly between -29 and 30% (figure 7). Positive trends occur in Ecuador, Peru, Brazil and Uruguay; while negative trends can be seen for Venezuela, Bolivia, Paraguay, Argentina, Brazil and Chile. The largest negative change can be found for the grid cells around the city of Talca in Chile (-60%).

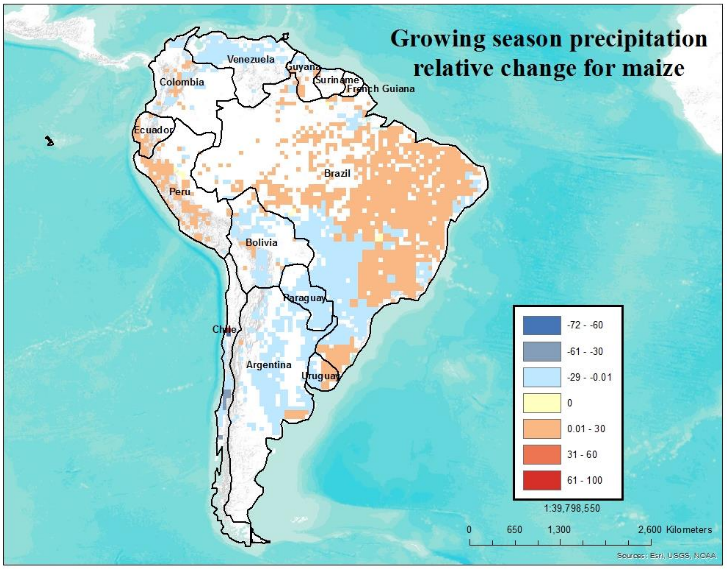
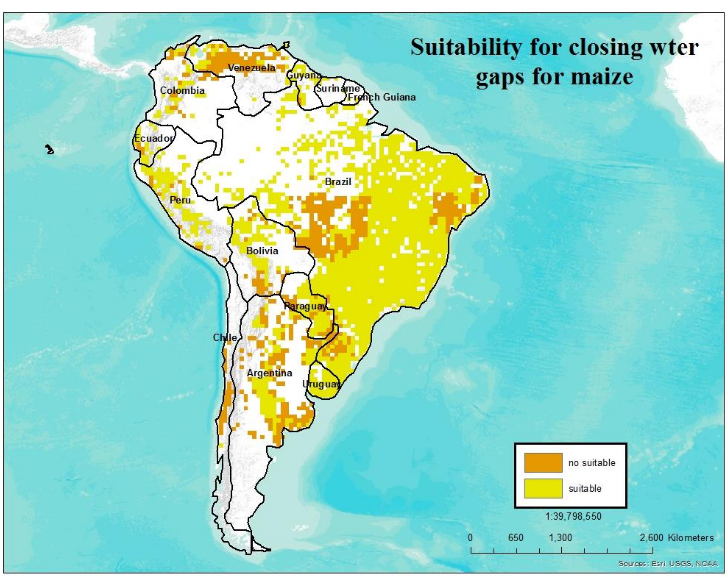


Figure7. Mean growing season precipitation relative change 2001-2050 for maize crop in South America.

4.1.3. Suitable zones for closing water yield gaps

For present and future climate, unsuitable zones are mostly located in Chile, Argentina, central and east Brazil over Caatinga ecoregion (WWF, 2012), Venezuela, and some points in Colombia, Bolivia, and Paraguay (figure 8, 9).

Negative suitability changes (figure 10) can be found for a few grid cells in Argentina and southern Brazil where suitability changed over time from suitable to not suitable. In Paraguay and some few grid cells in Brazil and Argentina the opposite change from not suitable to suitable can be seen. In general, the ability for closing the water gaps remains constant for maize for the study period.



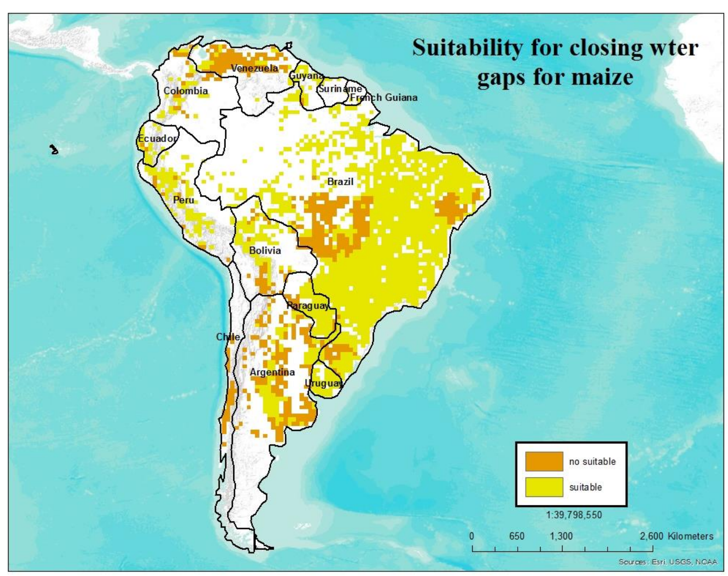


Figure8. Present suitable areas for closing yield water gap for maize crop in South America

Figure9. Suitable areas for closing yield water gap for crop maize for year 2050 in South America

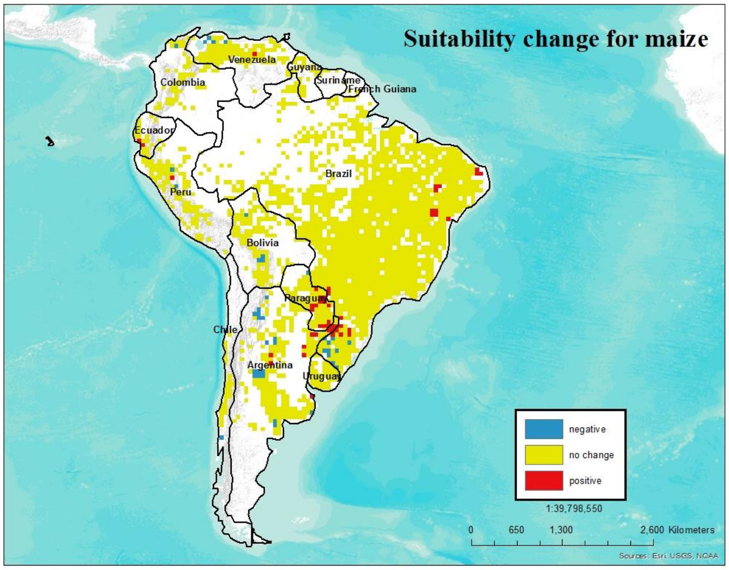


Figure10. Suitability change 2001-2050 for closing yield water gap for maize in South America

4.2. Wheat crop analysis in South America

4.2.1. Current and near future water yield gaps

The most important zones to improve yield in relative terms for wheat are mainly restricted to Andes mountain range with the exclusion of Colombia (figure11, 13), but also in Southeastern Bolivia and central part of Argentina. There are also three small regions in central-east and south of Brazil, the center of Chile, and north Venezuela with a large fYw. A belt of large fYw going from central Paraguay, southwards to the south of Argentina can also be seen. For these areas the fYw ranges between 62 and 100%.

In absolute terms, water yield gap in the above mentioned can reach up to 0.8738 kg/m^2 for present (figure 12) and 1.18 kg/m^2 for future (figure 14). The relative change in fYw displays a general decrease up to -29% between 2000 and 2050. Changes up to 100% occur in the center of Paraguay and south Argentina and Uruguay. (figure15).

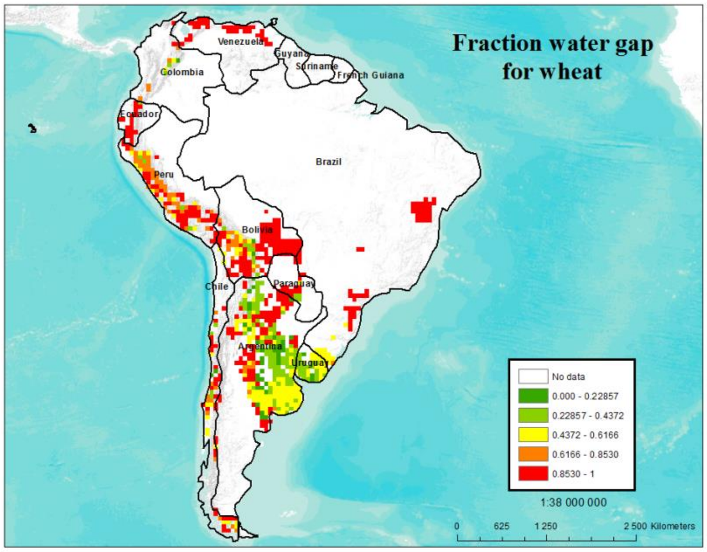


Figure11. Fraction water yield gap for wheat crop for year 2000 in South America.

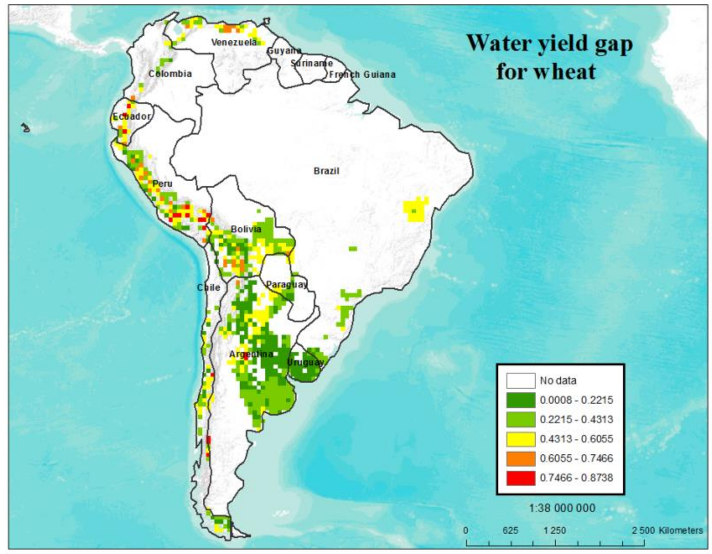


Figure12. Water yield gap for wheat crop for year 2000 in South America. Units in kg/m^2

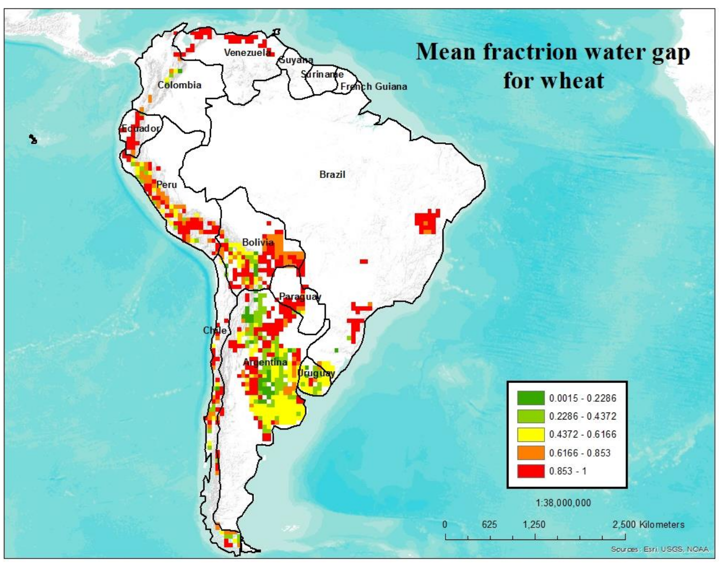


Figure13. Mean fraction water yield gap for wheat crop for year 2050 in South America.

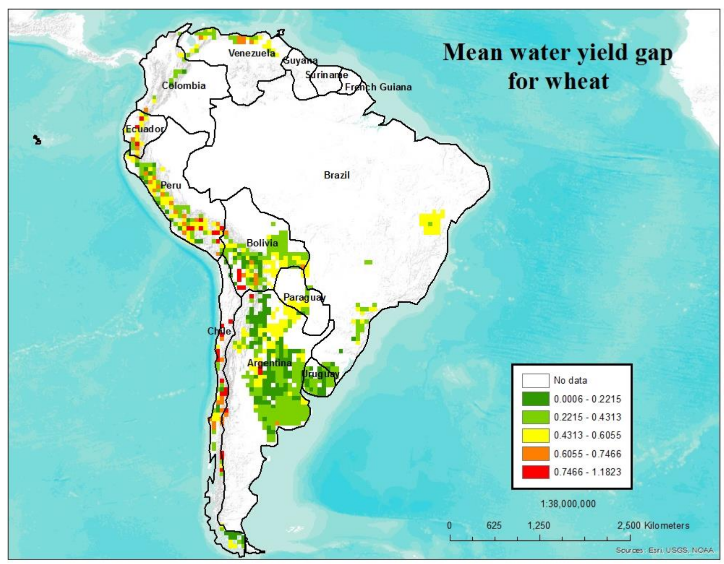


Figure14. Mean water yield gap for wheat crop for year 2050 in South America. Units in kg/m^2

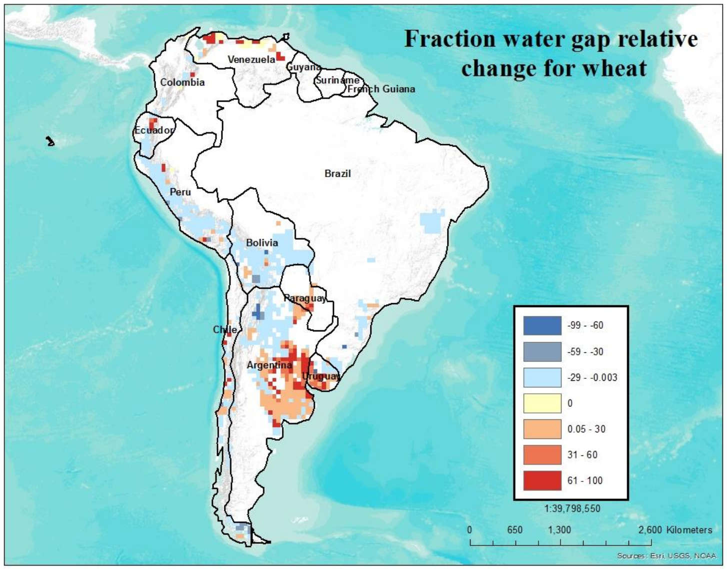


Figure15. Mean water gap relative change 2001-2050 for wheat crop in South America. Units in %.

4.2.2. Growing season precipitation relative change

GSP increases up to 30% in Ecuador, Peru, northwest Bolivia and Brazil. A decrease over time of the same order of magnitude also occurs in southern Bolivia, Paraguay, Argentina, Uruguay, Brazil and Chile. Higher changes between 60 and 100% take place in some points between Peru, Bolivia and Chile (figure 16).

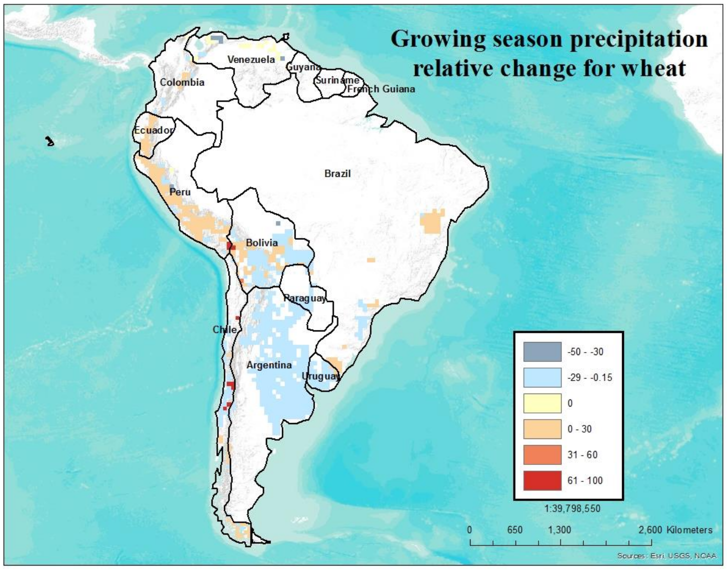


Figure16. Mean growing season precipitation relative change 2001-2050 for wheat crop in South America.

4.2.3. Suitable zones for closing water yield gaps

Current and future areas that present a restriction for improving yield gaps according to suitability are located in the south cone in South America (figure 17, 18) in Argentina, Chile, Uruguay, Paraguay and southwestern Bolivia. Negative changes in suitability over time are concentrated to Argentina with few grid cells in Paraguay, Uruguay and Venezuela (figure 19). On the other hand, most of the positive changes are located between Argentina and Uruguay showing a change from not suitable in the present to suitable in the future (figure 19).

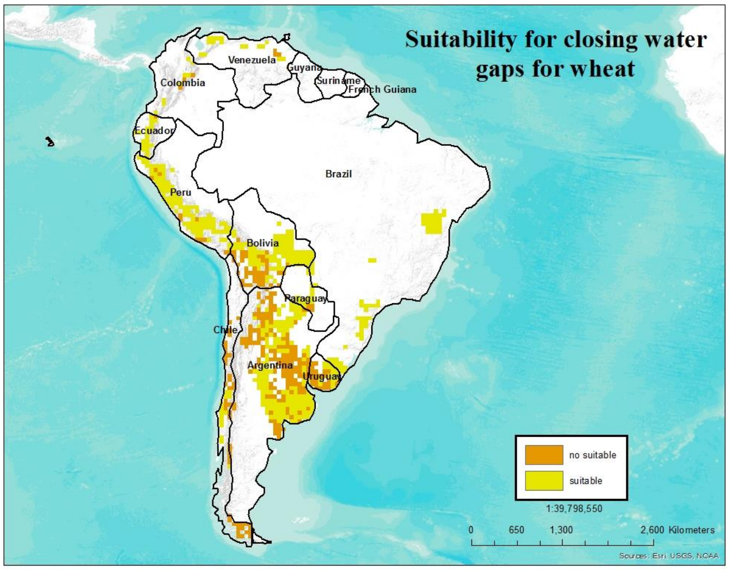


Figure17. Suitable areas for closing yield water gap for crop wheat for year 2050 in South America

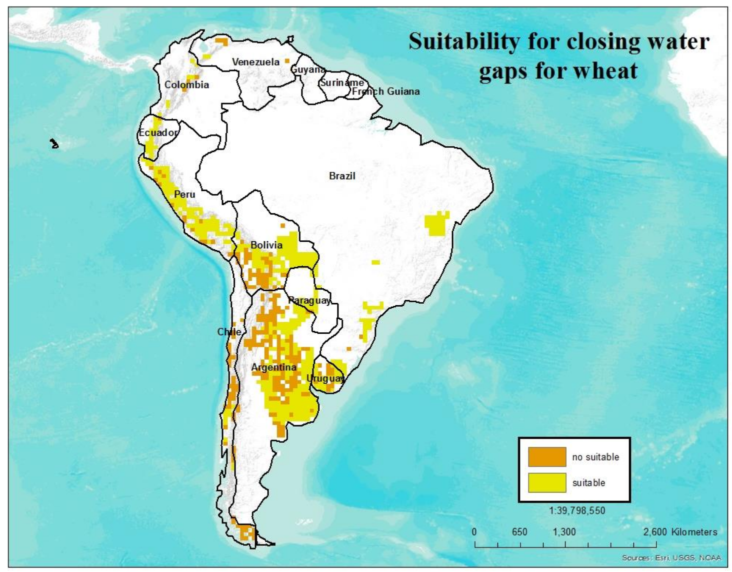


Figure18. Suitable areas for closing yield water gap for crop wheat for year 2050 in South America

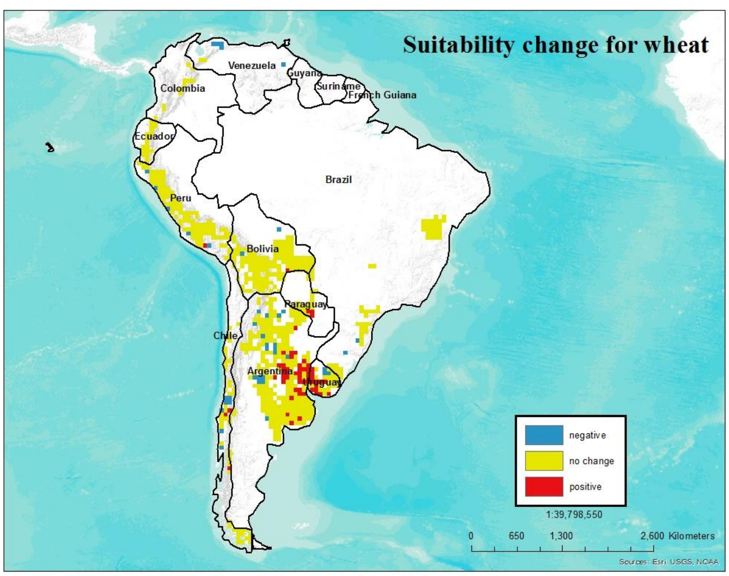


Figure19. Suitability change 2001-2050 for closing yield water gap for wheat in South America

4.3. Rice crop analysis for South America

4.3.1. Current and near future water yield gaps

For fractional water gap, the largest potential to improve yield for rice in relative terms can be found along the entire South American region with some regional exceptions in Brazil, Colombia and Ecuador (figure 20, 22). For these same areas the fYw ranges between 82 and 100%. In absolute terms, the largest water yield gaps achieve up to 1.1759 kg/m^2 for the present and 1.6078 kg/m^2 for the future, and are located mostly in the center east part of the region, midst Brazil, Bolivia, Paraguay and Uruguay (figure 21, 23).

The relative change in fYw presents a general decrease that achieves -19% for most of the rice territory. However, increases up to 10% can be found in Paraguay and Uruguay (figure 24).

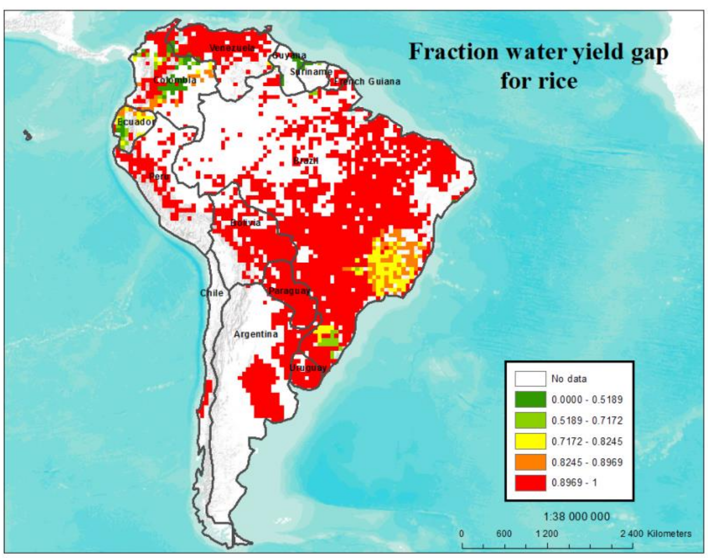


Figure20. Fraction water yield gap for rice crop for year 2000 in South America.

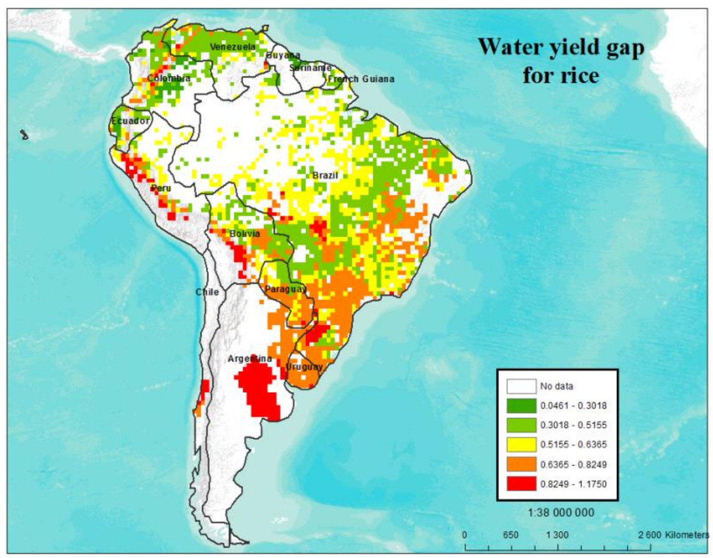


Figure21. Water yield gap for rice crop for year 2000 in South America. Units in kg/m^2

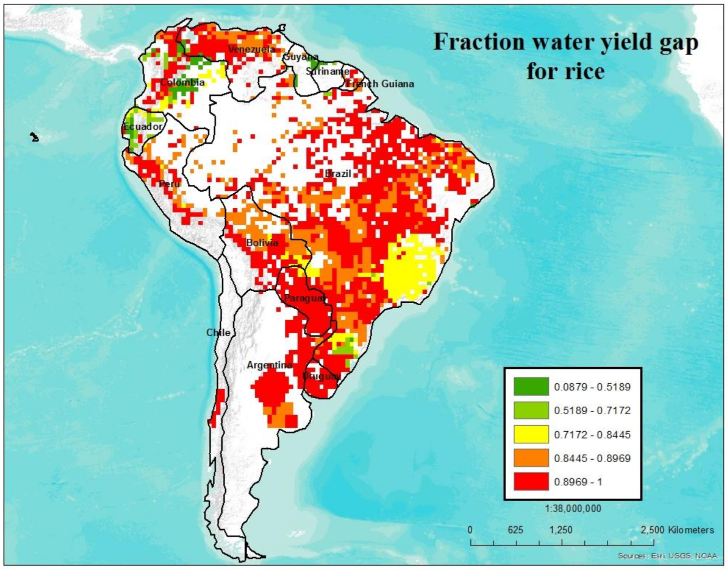


Figure22. Mean fraction water yield gap for wheat crop for year 2050 in South America.

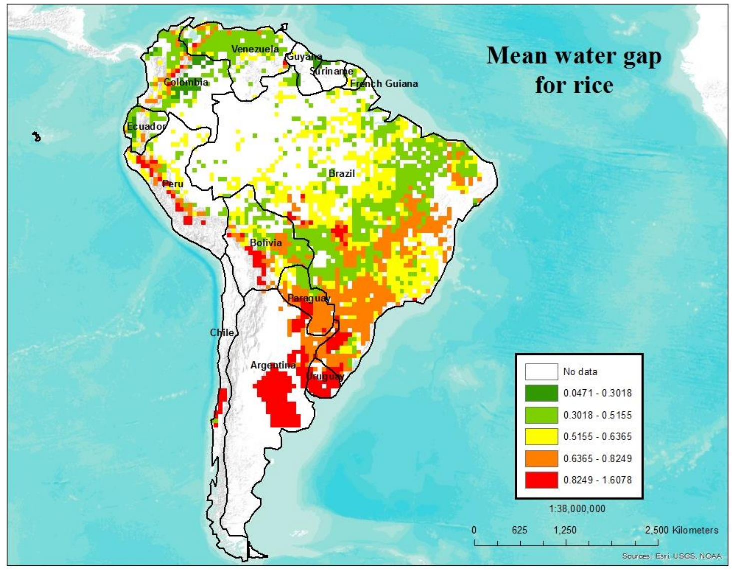


Figure23. Mean water yield gap for wheat crop for year 2050 in South America. Units in kg/m^2

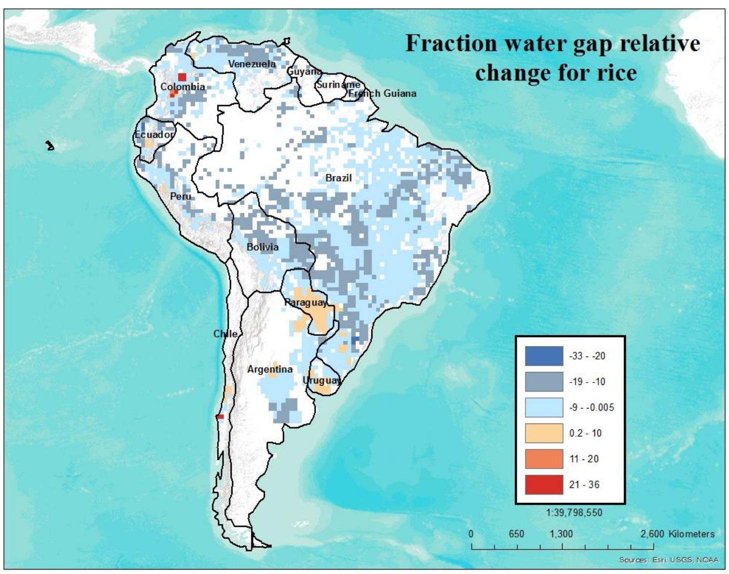


Figure24. Mean water gap relative change 2001-2050 for rice crop in South America. Units in %.

4.3.2. Growing season precipitation relative change

GSP displays positive and negative change throughout the region. Positive trends for precipitation of up to 17% occur in Colombia, Ecuador, Peru, Brazil, French Guiana, Uruguay and Argentina. Negative trends, on the other side, reaching at the most -30% are placed in Venezuela, Colombia, Bolivia, Brazil, Paraguay and Argentina. Highest negative changes are concentrated in a very limited area in the center of Chile.

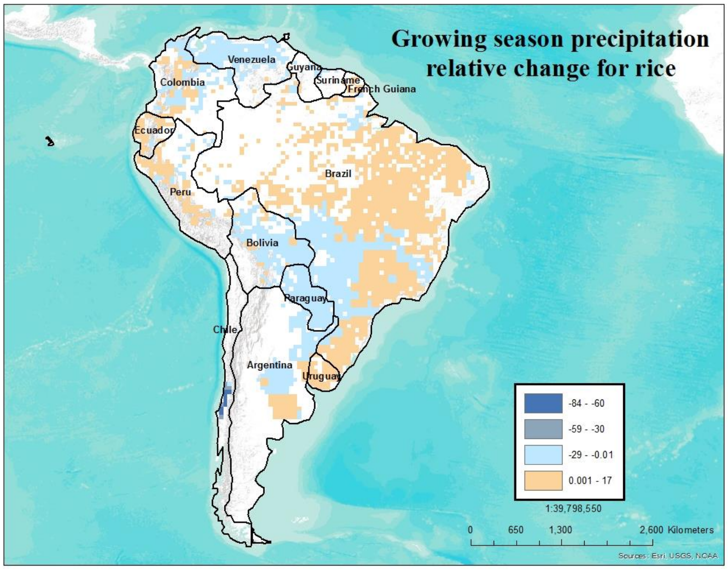
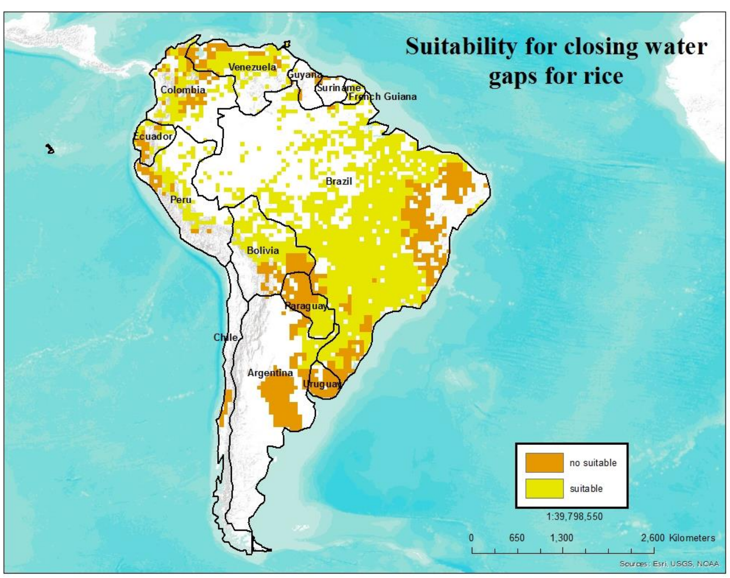


Figure25. Mean growing season precipitation relative change 2001-2050 for rice crop in South America. Units

4.3.3. Suitable zones for closing water yield gaps

Present and future suitability is mostly the same, showing no suitable areas in Argentina, Chile, Uruguay, Bolivia, Brazil, Venezuela, Colombia, Ecuador and Peru (figure 26, 27).

Suitability does not change over time for the majority of rice territory in South America. However, negative changes occur for some grid cells in Venezuela, Ecuador, Argentina and Paraguay. Positive changes also take place in Brazil and Uruguay (figure 28).



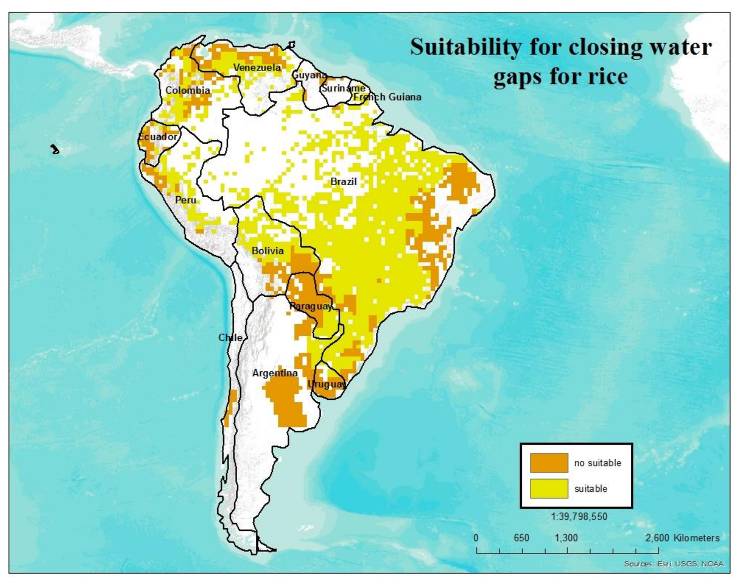


Figure26. Present suitable areas for closing yield water gap for rice crop in South America

Figure27. Suitable areas for closing yield water gap for crop rice for year 2050 in South America

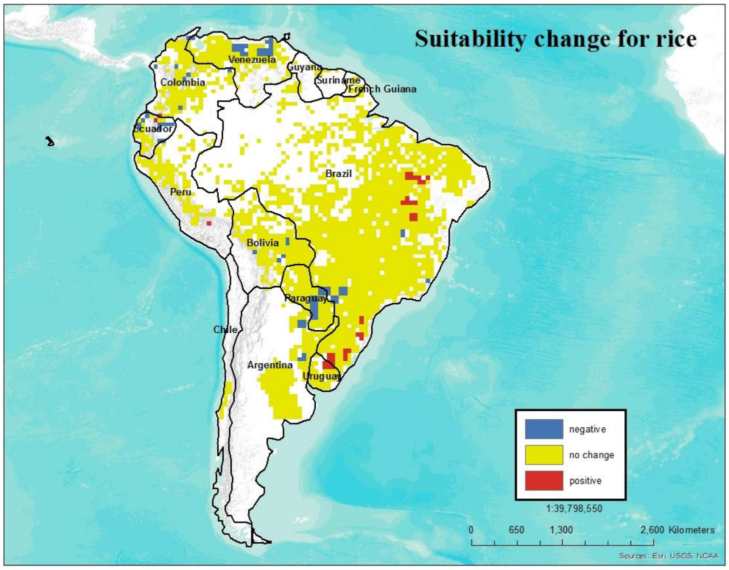


Figure28. Suitability change 2001-2050 for closing yield water gap for potato in South America

4.4. Potato crop analysis for South America

4.4.1. Current and near future water yield gaps

In relative terms, the most important areas to improve yield gaps are situated along the Andes mountain range from Venezuela until Argentina, with some exceptions in Colombia. Central part of Chile, southern part of Brazil, Bolivia and Paraguay, and the central zone in Argentina are also areas with high fraction fYw (figure 29, 31). For these areas the fYw goes from 58 to 100%. In absolute terms, the largest water yield gaps for present climate are 6.93 kg/m^2 and 7.86 kg/m^2 for future climate (figure 30, 32).

The relative change in fYw exhibits positive and negative variation for potato over time. Negative changes cover almost the entire area for potato and reach -21%. Positive change is higher but occurs only in four small areas: Paraguay, central Argentina, Uruguay and Chile. Highest fYw positive change, up to 100%, takes place in central Argentina (Figure33).

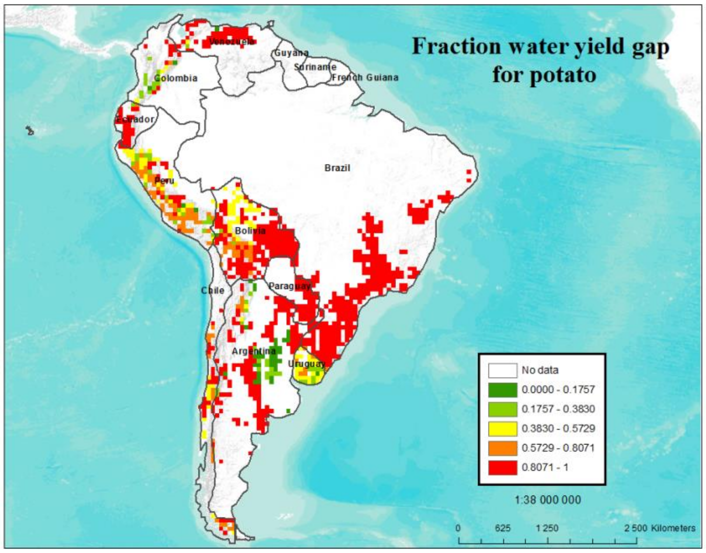


Figure29. Fraction water yield gap for potato crop for year 2000 in South America.

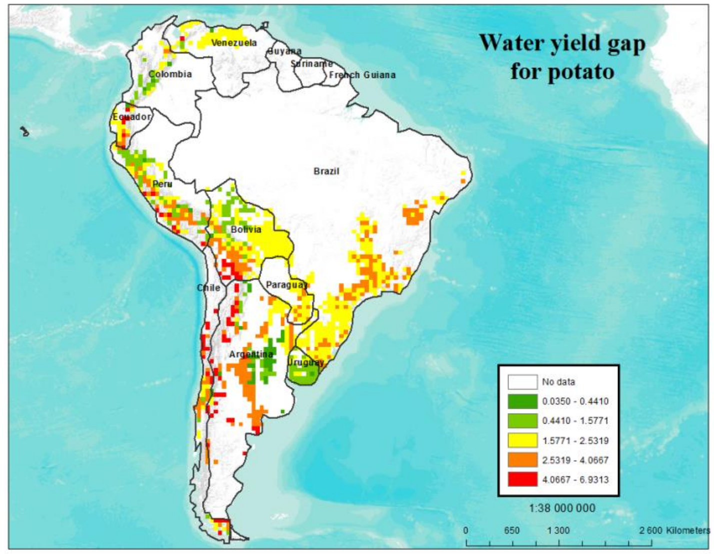


Figure30. Water yield gap for potato crop for year 2000 in South America. Units in kg/m^2

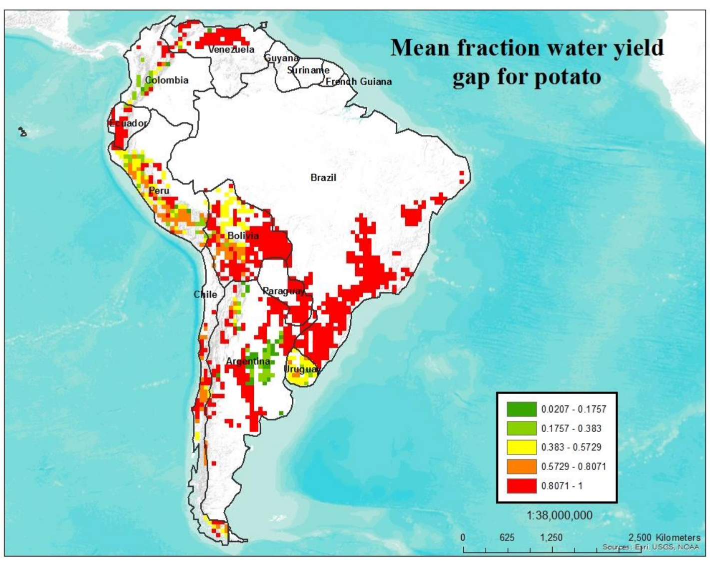


Figure31. Fraction water yield gap for potato crop for year 2050 in South America.

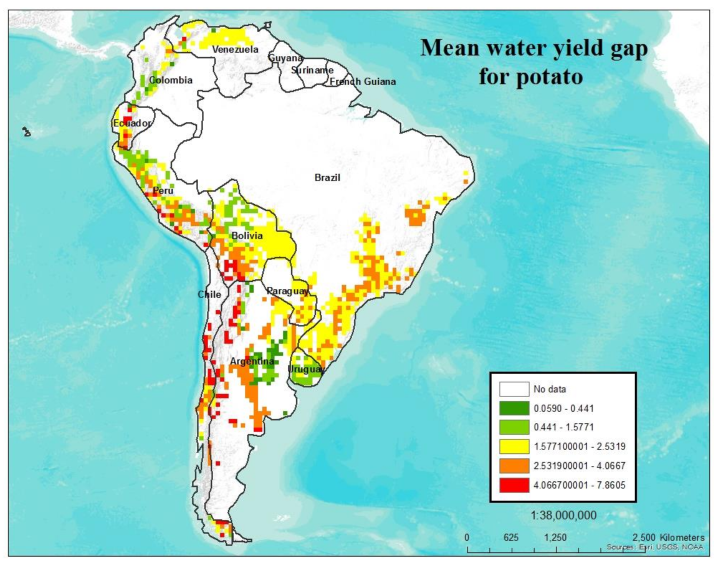


Figure32. Water yield gap for potato crop for year 2050 in South America. Units in kg/m^2

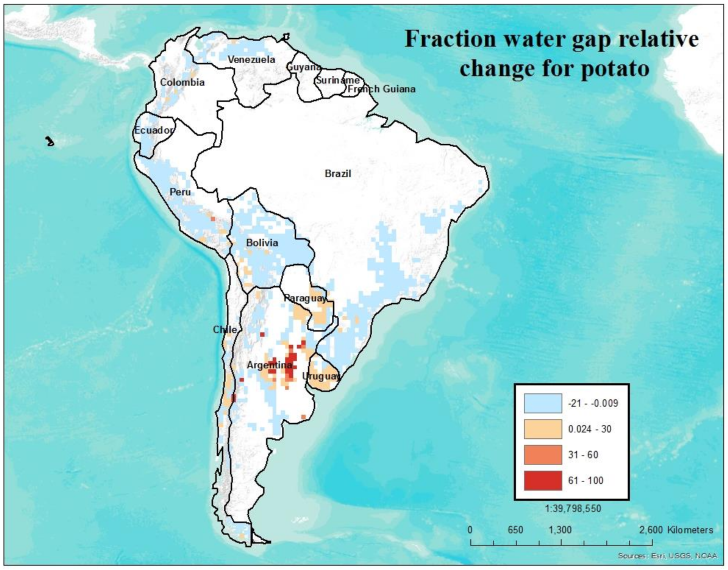


Figure33. Mean water gap relative change 2001-2050 for potato crop in South America. Units in %.

4.4.2. Growing season precipitation relative change

GSP displays positive or negative trends of the same scale over the entire subcontinent. Positive changes occur in Ecuador, Peru, Brazil and Uruguay; while negative changes take place in Bolivia, Argentina, Paraguay, Uruguay, Brazil, Colombia and Venezuela (Figure34).

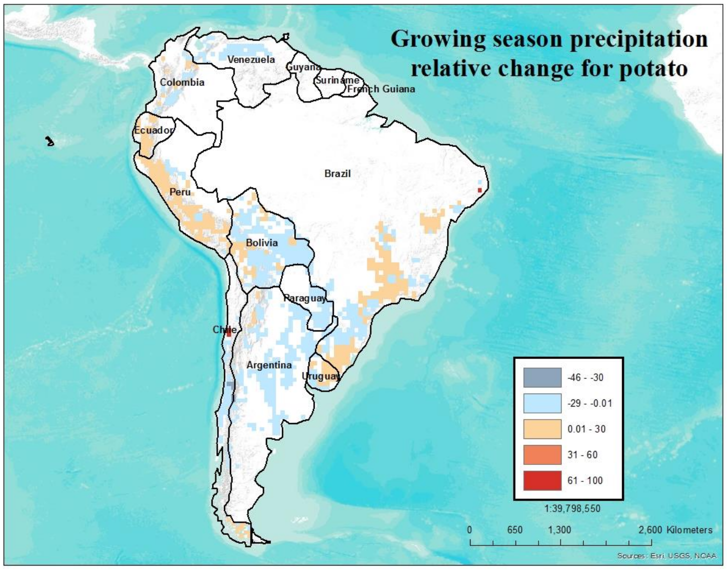


Figure34. Mean growing season precipitation relative change 2001-2050 for potato crop in South America.

4.3.3. Suitable zones for closing water yield gaps

For present and future climate, unsuitable zones for closing water yield gaps are located mainly in Chile, Bolivia, Argentina and Colombia with some few grid cells located also in Peru, Brazil and Uruguay (figure 35, 36).

Suitability change over time shows no change for almost the entire territory for this crop. Negative changes are restricted to few grid cells in Bolivia, Peru and Argentina and positive changes are present as isolated grid cells in Uruguay and Brazil (figure 37).

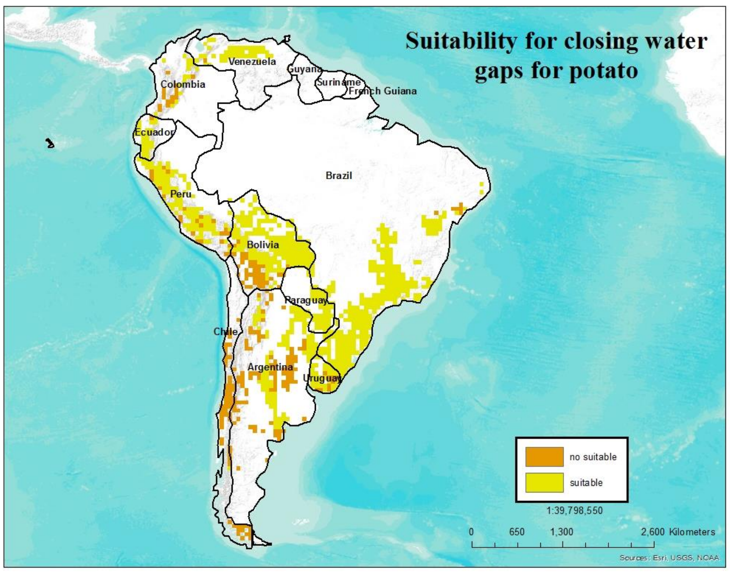


Figure35. Present suitable areas for closing yield water gap for potato crop in South America

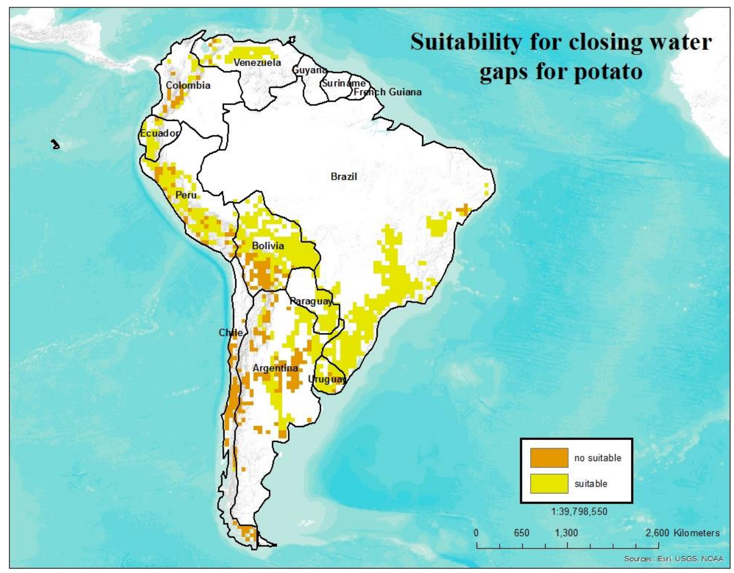


Figure36. Suitable areas for closing yield water gap for crop potato for year 2050 in South America

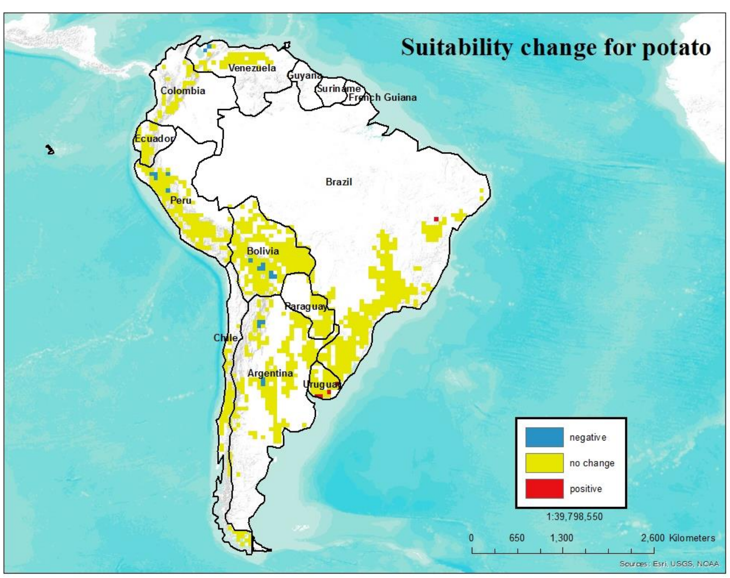


Figure37. Suitability change 2001-2050 for closing yield water gap for potato in South America

5. Discussion

5.1. Current fYw and Yw

The results of this study show the highest fYw and Yw for maize, wheat, rice and potato to be located along the Andes mountain range, central Chile, central Argentina and southeastern Brazil. High fYw and Yw are also present for the various crop in other regions but the location and extent of these regions are crop specific.

The water yield gap represents a fraction of the total yield gap (actual compared to potential), and earlier studies have mainly focused on this yield gap. Licker et al. (2010), for instance found large yield gaps for maize in regions restricted to the Andes in Colombia, Ecuador, Peru and Bolivia, and the northeastern part of Brazil, whereas fraction water yield gap (fYw) in this study were found for much larger areas. For example, the fYw for maize around Las Pampas and Brazil around Sao Paolo and Belo Horizonte was larger than the reported yield gap from Licker et al. (2010) (figure 2, 4). One reason for the diverging results could be explained by the different datasets used in this study compared to the one by Licker et al. (2010). By just looking at maps showing the actual (figure 1) and potential (in appendix figure 38) used in this study it becomes clear that these would generate yield gaps that are different from the ones found in Licker et al. (2010). Neumann et al. (2010), also present the same geographical distribution for maize yield gaps (in absolute terms). Compared to this study and the one by Licker (et al. 2010), the areal extent for where yield-gaps are reported by Neumann et al. (2010) are much smaller, with the largest yield gap zones located in east Brazil, central Argentina (Rosario), Ecuador and Venezuela, which mainly coincides with the results from this study. For rice and wheat both Licker et al. (2010) and Neumann et al. (2010) report very small areas with yield gap data making comparisons difficult.

This study has a slightly different purpose than these two comparing studies and therefore it is difficult compare the results especially as the results are based on different datasets. Also, as the two comparing studies are global it is difficult to compare the results from these studies without having access to the data. It is important to take into account the existence of several methods to assess potential yields and yield gaps, and that the resulting outcomes can differ by 50% or more

(Lobell et al. 2009). This is even more important for studies of yield gap under rainfed conditions (Lobell et al. 2009).

5.2. Trends in fYw

The results of this study reveal very high positive and negative changes for maize, wheat and potato water yield gaps concentrated in Paraguay, Uruguay and Argentina; and a general positive and negative low change for rice (figure 6, 15, 24, 33). Climate change is expected to impact yields in a considerable way (Lobell et al., 2011), as result of the combination of warming conditions and more variable rainfall (Magrin et al. 2014), in fact, it is likely to have negative impacts on average yields from 2030, and after 2050 these impacts would increase (Porter et al, 2014).

Changes in fYw over time depend on changes in both rainfed and irrigated yield. At the global scale it can be seen that for the model used in this study (LPJ-GUESS) the trends in yield are relatively similar for rainfed and irrigated crops for maize and wheat whereas for rice, the increase in future yield is much stronger for irrigated compared to rainfed crops (Rosenzweig et al., 2014). The analysis in this study is based on simulations performed using one crop model.

The study by Rosenzweig et al. (2014) also shows the large differences in the simulated response between crop models and the model mean changes in yield over time varies between crops. Their study reports model mean decreases around 25% in maize rainfed yields for year 2070-2099 in comparison to 1981-2010 baseline, located in the north-central part of the region and increases up to 50% for the Andes from Peru to Argentina, and the south cone. Similarly a decrease in up to 50% for the north-central part of the South America and a yield increment up to 50% for the Andes from Peru to Bolivia, and for the south cone were reported for wheat in the same study. Decreasing yields for rice of about 25% were found in Venezuela and Paraguay as well as increases up to 50% for the Andes from Ecuador to Argentina, and the south cone (Rosenzweig et al., 2014). Relative change results for fYw for the four crops in this study are partially consistent with the trends showed above. Along Andes mountain range it is clear a negative trend for fYw that could be partly explained by increases in rainfed high yields reported above however, this correlation is not that clear for the rest of the region. The results by Rosenzweig et al. (2014) represent the mean of a range of state-of-the art crop models (including LPJ-GUESS) but using different methods would lead to slightly different results. Jones and Thornton (2003) for example established a general reduction of 10% in maize production to year 2055 but with large regional differences.

One of the main uncertainties is associated to CO2 effect on plant physiology (Magrin et al, 2014). Maize for instance, as a C4 crop, is an efficient user of water and extraordinarily tolerant of high temperatures. It has a high rate of photosynthesis and would response positively to increases in atmospheric CO2 up to 520 ppm (Jones and Thornton, 2003; FAO, 2012; FAO, 2013).

Climate change affects agriculture in several ways, but agricultural expansion and/or intensification can also change climate locally, regionally or globally, as a result of land-surface feedbacks (Bonan, 1997; Stohlgren et al., 1998; Costa and Foley, 2000; Fu, 2003). This is not taken into account in this study.

5.3. GSP

The present study shows negative and positive relative change for GSP in South America for the fours crops. Negative changes (up to -29%) are located in Venezuela, Bolivia, Paraguay, Colombia, Argentina, Chile and south western Brazil for maize, wheat, rice and potato. Positive relative changes in GSP (up to 30%) occur in Colombia, Ecuador, Peru and Brazil. Uruguay presents both trends according to the crop (figure 7, 16, 25, 34).

The simulated changes depend on both on changes in precipitation over time as well as the simulated length of the growing period. These two factors cannot be disaggregated from the model results. Simulated length of the growing period will be affected by both the timing of sowing and the number of days between sowing and harvest. The latter depends on temperature sums and therefore decreases with increasing temperature.

5.4. Suitability

South America has a significant chance for improving crop yields as nutrient and water constraints are strong (Foley et al., 2011). The present study gives support to this with large regions with both large potential to close the water yield gap and with high levels of growing season precipitation (GSP). In this study unsuitable areas for improving rainfed crops were found to be concentrated in Bolivia, Argentina, Paraguay, Chile and Uruguay; however there are other important areas depending on the crop. Positive suitability change over time for all four crops can be found in Uruguay, Brazil, Argentina and Paraguay; while negative suitability change is located in Argentina, Bolivia, Venezuela and Brazil. The results from this study partly agrees with the results from Foley et al. (2011) who found important water limited areas for maize situated in the east central part of Brazil, from Teresina southwards until Sao Paulo, and also in the south near Uruguay around Porto Alegre, as well as in northern Argentina, close to San Miguel de Tucuman.

Suitability is on one hand depending on the availability of water. This means that if less than the required water is available during the crop growing season, then the region is considered unsuitable for growing crops. On one hand this might under estimate the suitable area, as rainwater can be collected over a larger region than what is being used for crops, surface water and ground water are not taking into account either. However, GSP represents the total amount of water available during the growing season and there might be evaporative losses of water that are not taken into account in this study. Looking at only the amount of available water, the suitable areas for irrigation extend to almost the entire continent for all crops (in the appendix figure 39-40; 42-43; 45-46; 48-49). But in many regions the fYw is already low (figure 2, 4; 11, 13; 20, 21; 29, 30) and the gain for adding irrigation to these regions is limited. Therefore the regions of low yield gaps were selected as unsuitable, generating a much smaller area where irrigation is suitable for closing the water yield gap. On average yields in rainfed agriculture systems are commonly 50% or less of yield potential, leaving plenty of room for improvement (Lobell et al., 2009). In this study the classification of suitability varied between crops and according to previous classification of fYw and GSP. For wheat, maize and potato suitable areas present a fYw that ranges from 38 to 100%, whereas for rice it was between 72 and 100%. This means a potential to increase yield by including irrigation (on top of optimal nutrients) to ranging from 38% (maize, wheat, potato) to 72% (rice). Choosing other ranges would alter the results slightly but in general would have given similar results.

Suitability results in this study demonstrate that the four crops have areas with great potential to increase yield combined with high levels of precipitation. In this scenario, a gradual change from rainfed to irrigated systems would help to close yield gaps. Elliot et al. (2014) states that in South America, irrigation water demand is lower than available renewable water, and this latter comes essentially from rain water (CIAT, 2013). Therefore, the region presents positive trends for irrigation adaptation potential (Elliott et al., 2014). In the context of climate change, yield reduction will be alleviated by expansion of irrigation. In fact, if a maximum conversion between these two systems would be fulfilled, yields will stay at least in the same levels, but in many areas they will even rise (Elliott et al., 2014).

But water management is only one of the factors for stagnation in reaching crop yield potential in the region. One of the main concerns in this field is high expenses of irrigation projects and the cost-benefit relationship between this investment and potential production. Soil degradation and erosion, diseases and pests, fertilizer use, lack of higher yielding varieties, droughts, frosts, market and political challenges, financial constraints including access to credit or insurance systems (Deryng et al. 2011; Magrin et al., 2014, Porter et al., 2014) are needed to be overcome, in order to attain the potential South America has in the agricultural sphere.

5.5. Limitations and uncertainties

Some of the limitations of this study include the use of different sources of data for potential, rainfed yields and model outputs; and uncertainties related to these datasets. In the crop model comparison carried out by Rosenzweig et al. (2014), LPJ-GUESS model presents the highest changes for crop production among six other models used. Therefore, this model outputs can be overestimating the results in this study. Another limitation of the study is that it only looks at the added potential of irrigation to crops receiving optimum (or high) levels of nutrients. Also it is assumed in this study that simulated irrigated yield can be considered to be the potential. This is likely not always the case. Further, the results are based on the mean of 5 different GCMs. This was done to minimize the uncertainty that would come from selecting only one GCM, as simulation results are known to vary greatly depending on the GCM used (Ahlström et al., 2012).

Some aspects need to improve in order to better the area of yield gap studies. These include: improvement of datasets required to assess yield gap, potential gap, actual yield and make these more accessible; create a common protocol to assess yield gap in order to avoid the differences in the current results, refine statistical information in a country level with spatial information, more detailed information on historical and current land use, downscaling of yield gaps assessment to regional or national level, improve model CO_2 and N parameterization, among others (van Ittersum et al. 2012; Lobell et al., 2009; Rosenzweig et al. 2014).

5.6. Policy implications

South America presents great potential to improve rainfed yields and consequently to close water yield gaps. As agriculture water demand is lower than renewable available water, the region has an interesting opportunity for irrigation adaptation in a climate change context. Suitable areas for maize, wheat and potato present an important chance for improving rainfed crops by irrigation between 38 and 100%, while for rice this chance is even larger 72 to 100%. Unsuitable areas for improving rainfed yields based on fYw and GSP are located in Bolivia, Argentina, Paraguay, Chile and Uruguay, with very few areas presenting a change over time. In terms of yields, important attention should be directed to the areas that expose highest changes for fYw, Paraguay, Uruguay and Argentina. Even though South America has and will continue to have a surplus of water supply, it is necessary to pay attention to the potential impacts of positive and negative changes this study presents for GSP.

6. Conclusion

In South America, the highest fYw and Yw for maize, wheat, rice and potato coincide along the Andes mountain range, central Chile, central Argentina and southeaster Brazil. These regions extend to other regions for all crops, and the location of these regions is highly crop specific.

Most important changes in fYw between year 2000 and 2050 are concentrated to Paraguay, Uruguay and Argentina for maize, wheat and potato. Rice presents a different situation with a low general change for its yield area.

Negative relative change for GSP in South America occur in Venezuela, Bolivia, Paraguay, Colombia, Argentina, Uruguay, Chile and south western Brazil for maize, wheat, rice and potato. Positive relative changes in GSP occur in Colombia, Ecuador, Peru, Brazil and Uruguay for the four crops.

Unsuitable areas for improving rainfed crops are concentrated in Bolivia, Argentina, Paraguay, Chile and Uruguay, but there are other important areas depending on the crop. In general terms, positive suitability change from 2000 to 2050 for the four crops is situated in Uruguay, Brazil, Argentina and Paraguay; while negative suitability change is located in Argentina, Bolivia, Venezuela and Brazil.

South America presents a considerable potential to improve rainfed crops by adding irrigation to the cropping system, but the subcontinent also presents social and economic challenges that may limit their potential. Changes in suitability over time reflect both changes in climate as well as the resulting effect on the length of the growing season and yield.

7. References

Ahlström, A., G. Schurgers, A. Arneth and B. Smith (2012) Robustness and uncertainty in terrestrial ecosystem carbon response to CMIP5 climate change projections. *Environmental Research Letters*, pp. 1-9

Bonan, G.B. (1997) Effects of land use on the climate of the United States. *Climatic Change*, pp. 449–486

Bondeau, A., P. Smith, S. Zaehle, S. Schaphoff, W. Lucht, W. Cramer, D. Gerten, H. Lotze-Campen, C. Müller, M. Reichstein, and B. Smith (2007) Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Change Biology*, pp. 679–706.

Centro Internacional de Agricultura Tropical (CIAT) (2013) Eco-Efficiency: From vision to reality, Colombia.

Centro Internacional de la Papa (CIP) (1999). *Producción de tubérculos-semillas de papa*, [Online], Lima, Perú. Available at: http://books.google.com.ec/books?id=2dBc4aaogXIC&pg=PT16&lpg=PT16&dq=produccion+de+papa+en+america+del+sur&source=bl&ots=slbx9k6EWs&sig=mRhB67xOp_Bc8FoXSLqTR8WmOtE&hl=es-419&sa=X&ei=qrxTVIXUNYOuOPDEgNAC&ved=0CDMQ6AEwBA#v=onepage&q&f=true. [31 October 2014].

Centro Internacional de la Papa (CIP) (n.d.) Potato facts and figures, [Online], *Agricultural research for development*. Available at: http://cipotato.org/potato/facts/ [31 October 2014].

Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J.W. and M.W. (2013) Long-term Climate Change: Projections, Commitments and Irreversibility. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. United Kingdom and New York.

Costa, M.H. and J.A. Foley (2000) Combined effects of deforestation and doubled atmospheric CO2 concentrations on the climate of Amazonia. *Journal of Climate,* pp. 18–34.

Cubasch, U., D. Wuebbles, D. Chen, M.C. Facchini, D. Frame, N. Mahowald, and J.-G.Winther (2013) Introduction. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. United Kingdom and New York.

Deryng, D., W.J. Sacks, C.C. Barford, and N. Ramankutty (2011) Simulating the effects of climate and agricultural management practices on global crop yield. *Global Biogeochemical Cycles*, pp.1-18

Elliott, J., D. Deryng, C. Müller, K. Frieler, M. Konzmann, D. Gerten, M. Glotter, M. Flörke, Y. Wada, N. Best, S. Eisner, B.M. Fekete, C. Folberth, I. Foster, S. N. Gosling, I. Haddenland, N. Khabarov, F. Ludwig, Y. Masaki, S. Olin, C. Rosenzweig, A.C. Ruane, Y. Satoh, E. Schmid, T. Stacke, Q. Tang, and D. Wisser (2014) Constraints and potentials of future irrigation water availability on agricultural production under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, pp. 3239–44.

Flato, G., J. Marotzke, B. Abiodun, P. Braconnot, S.C. Chou, W. Collins, P. Cox, F. Driouech, S. Emori, V. Eyring, C. Forest, P. Gleckler, E. Guilyardi, C. Jakob, V. Kattsov, C.R. and M.R. (2013) Evaluation of Climate Models. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assess- ment Report of the Intergovernmental Panel on Climate Change*. United Kingdom and New York.

Foley, J., N. Ramankutty, K.a. Brauman, E.S. Cassidy, J.S. Gerber, M. Johnston, N.D. Mueller, C. O'Connel, D.K. Ray, P.C. West, C. Balzer, E.M. Bennett, S.R.Carpenter, J. Hill, C. Monfreda, S. Polasky, J. Rockström, J. Sheehan, S. Siebert, D. Tilman, and D.P.M. Zaks (2011) Solutions for a cultivated planet. *Nature*, pp. 337–42.

Food and Agriculture Organization (FAO) (2008) América Latina, [Online], *Año Internacional de la Papa*. Available at: http://www.fao.org/potato-2008/es/mundo/america_latina.html [31 October 2014].

Food and Agriculture Organization (FAO) (2012) Crop yield response to water, Rome, 1-505

Food and Agriculture Organization (FAO) (2013) Crop water information: maize. *FAO water*, [Online], Available at: http://www.fao.org/nr/water/cropinfo_maize.html [03 November 2014].

Food and Agriculture Organization (FAO) (2014a) Crop prospects and food situation. *Global information and early warning system on food and agriculture*. Rome-Italy.

Food and Agriculture Organization (FAO) (2014b) Length of the growing season, [Online], Available at: http://www.fao.org/nr/climpag/cropfor/lgp_en.asp. [28 October 2014].

Food and Agriculture Organization (FAO) (n.d.a) Wheat in the world, [Online], Available at: http://www.fao.org/docrep/006/y4011e/y4011e04.htm [29 October 2014].

Food and Agriculture Organization (FAO) (n.d.b) Seguridad alimentaria y arroz en América Latina y el Caribe, [Online], Available at: http://agr.unne.edu.ar/fao/chile-ppt/SATecnologia-Graziano Chillan.pdf [30 October 2014].

Fu, C. (2003) Potential impacts of human-induced land cover change on East Asia monsoon. *Global and Planetary Change*, pp. 219–229.

Global crop diversity trust (n.d.) Priority crops: maize, [Online], Available at: http://www.croptrust.org/content/maize [21 October 2014].

HarvestChoice (2010) Measuring growing seasons, [Online], *International Food Policy Research Institute and University of Minnesota*. Available at: http://harvestchoice.org/labs/measuring-growing-seasons. [15 October 2014].

Hundertmark, W. and T. Facon (n.d.) Options for effective rice water management, [Online], *FAO corporative document repository*. Available at: http://www.fao.org/docrep/006/y4751e/y4751e0j.htm [03 November 2014].

Hunter College of the City University of New York (n.d.) How to choose a projection, [Online], Available at: http://www.geo.hunter.cuny.edu/~jochen/gtech201/lectures/lec6concepts/map coordinate systems/how to choose a projection.htm. [15 October 2014].

Jones, P. and P. Thornton (2003) The potential impacts of climate change on maize production in Africa and Latin America in 2055. *Global Environmental Change*, pp. 51–59.

Jones, P. and P. Thornton (2009) Croppersto livestock keepers: livelihood transitions to 2050 in Africa due to climate change. *Environmental Science & Policy*, pp. 427-437.

Kiple, K. and K. Connè Ornelas (2000) Potatoes (White). *The Cambirdge World History of Food*. Cambridge: The press syndicate of The university of Cambridge, pp. 187-201

Leff, B., N. Ramankutty and J. Foley (2004) Geographic distribution of major crops across the world. *Global Biogeochemical Cycles*, pp. 1-27

Licker, R., M. Johnston, J.A. Foley, C. Barford, C.J. Kuchrik, C. Monfreda, and N. Ramankutty (2010) Mind the gap: how do climate and agricultural management explain the "yield gap" of croplands around the world? *Global Ecology and Biogeography*, pp. 769–782.

Lindeskog, M., A. Arneth, A. Bondeau, K. Waha, J. Seaquist, S. Olin, and B. Smith (2013) Implications of accounting for land use in simulations of ecosystem carbon cycling in Africa. *Earth System Dynamics*, pp. 385–407.

Lobell, D.B., K.G. Cassman, and C.B. Field (2009) Crop Yield Gaps : Their Importance, Magnitudes, and Causes. *NCESR Publications and Research*. pp. 1-27

Lobell, D.B., W. Schlenker, and J. Costa-Roberts (2011) Climate trends and global crop production since 1980. *Science*, pp. 616–620.

Magrin, G., C. Gay García, D. Cruz Choque, J.C. Giménez, A.R. Moreno, G.J. Nagy, C.N. and A.Villamizar (2007) Latin America. Climate Change 2007: *Impacts, Adaptation and Vulnerability. Contribution ofWorking Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds.*, Cambridge University Press, Cambridge, UK, pp. 581-615.

Magrin, G.O., J.A. Marengo, J.-P. Boulanger, M.S. Buckeridge, E. Castellanos, G. Poveda, F.R. Scarano, and S. Vicuña, 2014. Central and South America. In Cambridge University Press, ed. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandre*. Cambridge, United Kingdom and New York, NY, USA, pp. 1499–1566.

Mast, M. and M. Pawlak (n.d.) Absolute change and percentage change, [Online], Available at: http://www.math.umb.edu/~joan/MATHQ114/change.htm. [20 October 2014]

Monfreda, C., N. Ramankutty, and J.A.Foley (2008) Farming the planet. Part 2: Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochemical Cycles 22*, pp. 1-19.

Morris, M.L. and M.A. López-pereira (2000) Impactos del mejoramiento de maíz en América Latina *1966-1997*. *International Maize and Wheat Improvement Center.* Mexico, pp. 1-55

Mueller, N.D., J.S. Gerber, M. Johnston, D.K. Ray, N. Ramankutty, and J.A. Foley (2012) Closing yield gaps through nutrient and water management. *Nature*, pp. 254–7.

Neumann, K., P.H. Verburg, E. Stehfest and C. Müller (2010) The yield gap of global grain production: A spatial analysis. *Agricultural Systems*, pp.316–326.

Olin, S., G. Schurgers, M. Lindeskog, D. Wårlind, B. Smith, P. Bodin, J. Holmér and A. Arneth (accepted) The impact of atmospheric CO_2 and N management on simulated yields and tissue C:N in the main wheat regions of Western Europe. *Biogeosciences Discussion.*

Ortiz, R. (2012) El cambio climático y la producción agrícola, *Banco Interamericano de Desarrollo*. pp. 1-41

Porter, J.R., L. Xie, A.J. Challinor, K. Cochrane, S.M. Howden, M.M. Iqbal, D.B. Lobell, and M.I. Travasso (2014) Food security and food production systems. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press*, Cambridge, United Kingdom and New York, NY, USA, pp. 485-533.

Riahi, K., S. Rao, V. Krey, C. Cho, V. Chirkov, G. Fischer, G. Kindermann, N. Nakicenovic, P. Rafal (2011) RCP 8.5—A scenario of comparatively high greenhouse gas emissions. *Climatic Change*, pp. 33–57.

Ricepedia (n.d.) Latin America and the Carribean, [Online], Available at: http://ricepedia.org/rice-around-the-world/latin-america-and-the-caribbean [30 October 2014].

Rosenzweig, C., J. Elliot, D. Deryng, A.C. Ruane, C. Müller, A. Arneth, K.J. Boote, C. Forlberth, M. Glotter, N. Khabarov, K. Neumann, F. Piontek, T.A.M. Pugh, E. Schmid, E. Stehfest, H. Yang, and J.W. jones (2014) Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proceedings of the National Academy of Sciences of the United States of America*, pp.3268–73.

Rowhani, P., D.B. Lobell, M. Linderman, and N. Ramankutty (2011) Climate variability and crop production in Tanzania. *Agricultural and Forest Meteorology*, pp. 449–460.

Seo, S.N. and R. Mendelsohn (2008) An analysis of crop choice: Adapting to climate change in South American farms. *Ecological Economics*, pp. 109–116.

Smith, B., I. Colin Prentice, and M.T. Sykes (2001) Representation of vegetation dynamics in the modelling of terrestrial ecosystems: comparing two contrasting approaches within European climate space. *Global Ecology and Biogeography*, pp. 621–637.

Smith, B., D. Wårlind, A. Arneth, T. Hickler, P. Leadley, J. Slitberg and S. Zaehle (2014) Implications of incorporating N cycling and N limitations in primary production in an individual-based dynamic vegetation model. *Biogeosciences*, pp. 2027–2054.

Stohlgren, T.J., T.N. Chase, R.A. Pielke, T.G.F. Kittel, and J.S. Baron (1998) Evidence that local land use practices influence regional climate, vegetation, and stream flow patterns in adjacent natural areas. *Global Change Biology*, pp. 495–504.

Tilman, D., C. Balzer, J. Hill, and B.L. Befort (2011) Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, pp. 20260–4.

United Nations (2009) World Population Prospects. *The 2008 Revision Highlights*, New York.

United States Department of Agriculture (USDA) (2015) Global Crop Production Analysis, [Online], Available at: http://www.pecad.fas.usda.gov/ [25 Janury 2015].

Universidad Austral (n.d.) El comercio de trigo entre Brasil y Argentina, [Online], Available at: http://www.austral.edu.ar/cienciasempresariales-ceag/2014/06/29/el-comercio-de-trigo-entre-brasil-y-argentina/ [27 October 2014].

Van Ittersum, M.K., K.G. Cassman, P. Grassini, J. Wolf, P. Tittonell, and Z. Hochman (2012) Yield gap analysis with local to global relevance—A review. *Field Crops Research*, pp. 4–17.

Vuuren, D.P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G.C. Hurtt, T. Kram, V. Krey, J.F Lamarque, T. Masui, M. Meinshausen, N. Nakicenovic, S.J. Smith, and S.K. Rose (2011) The representative concentration pathways: an overview. *Climatic Change*, pp. 5–31.

Waha, K., L.G.J. van Bussel, C. Müller and A. Bondeau (2012) Climate-driven simulation of global crop sowing dates. *Global Ecology and Biogeography*, pp. 247–259.

World Wildllife Fund (WWF) (2012) Ecoregions of Brazil, [Online] Available at: http://www.eoearth.org/view/article/51cbf3b27896bb431f6adc3e/ [03 November 2014].

Xia, J., Z. Yan and P. Wu (2012) Multidecadal variability in local growing season during 1901–2009. *Climate Dynamics*, pp.295–305.

You, L., Z. Guo, J. Koo, W. Ojo, K. Sebastian, M.T. Tenorio, S. Wood, U. Wood-Sichra (2010) Spatial Production Allocation model (SPAM), [Online], Available at: http://mapspam.info/data/ [29 July 2014].

Zhang, X. and X. Cai (2011) Climate change impacts on global agricultural land availability. *Environmental Research Letters*, pp. 357–374.

Zucchini, F. (n.d.) Harina de trigo. *Secretaría de agricultura, ganadería, pesca y alimentos*, [Online] Available at: http://www.alimentosargentinos.gov.ar/contenido/revista/ediciones/28/Harina_trigo.htm [27 October 2014].

8. Appendix

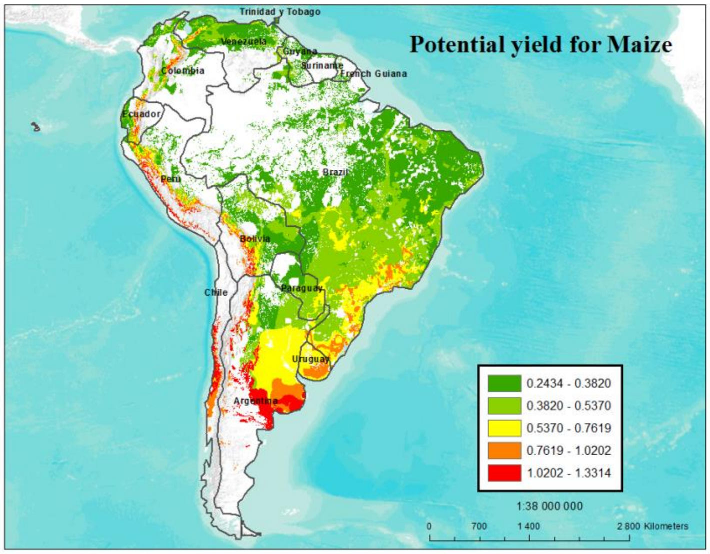


Figure38. Potential yield for maize in South America for year 2000. In kg/m^2. Modified from Monfreda et al. (2008) .

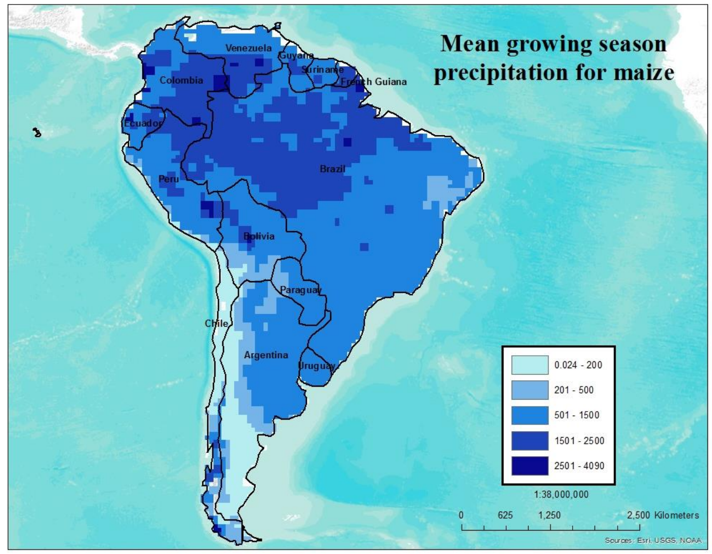


Figure39. Mean growing season precipitation for maize crop for year 2001 in South America. In kg/m^2

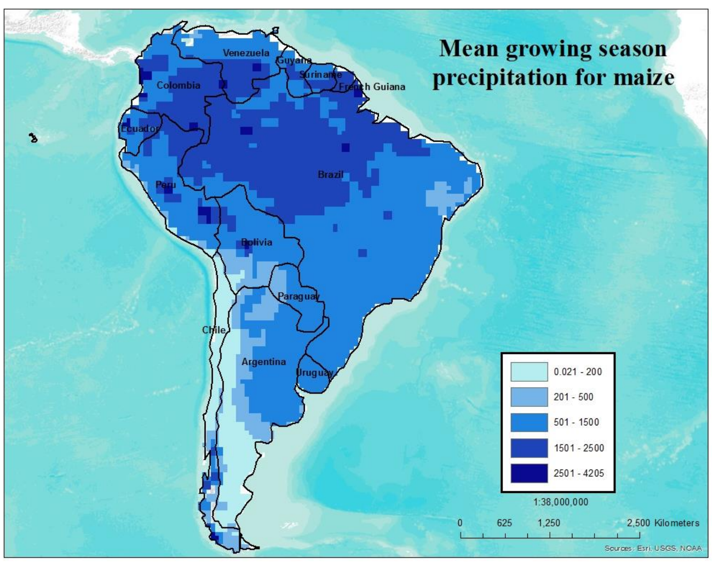


Figure40. Mean growing season precipitation for maize crop for year 2050 in South America. In kg/m^2

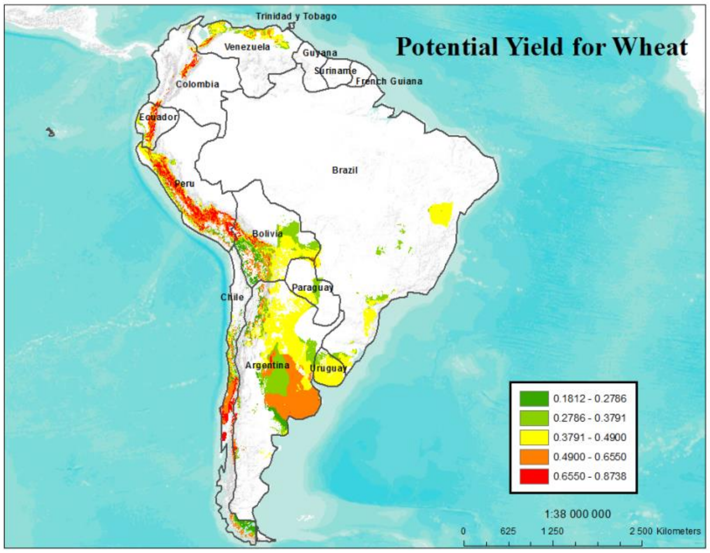


Figure41. Potential wheat for rice in South America for year 2000. In kg/m^2. Modified from Monfreda et al. (2008).

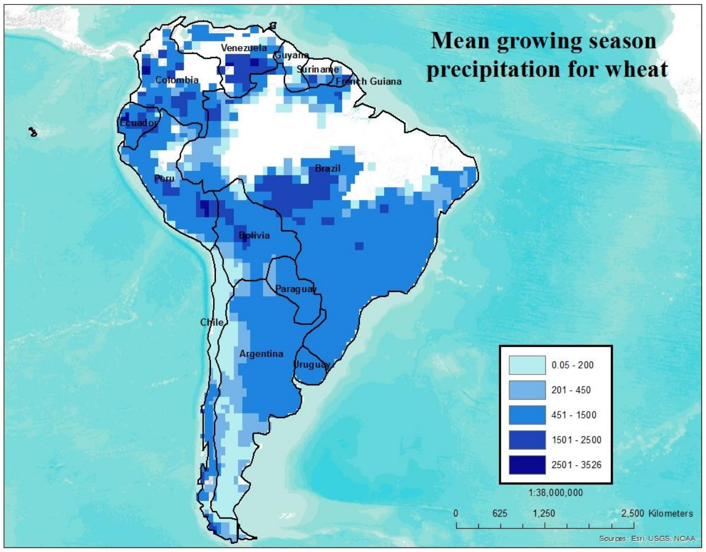


Figure42. Mean growing season precipitation for wheat crop for year 2001 in South America. In kg/m^2

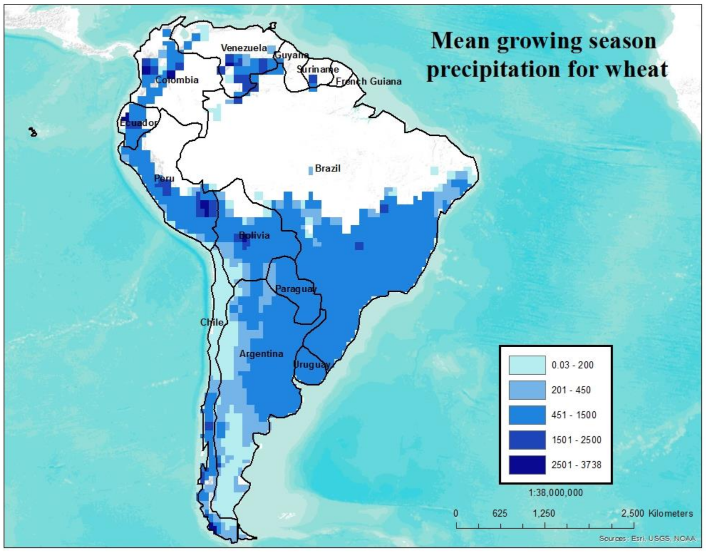


Figure43. Mean growing season precipitation for wheat crop for year 2050 in South America. In kg/m^2

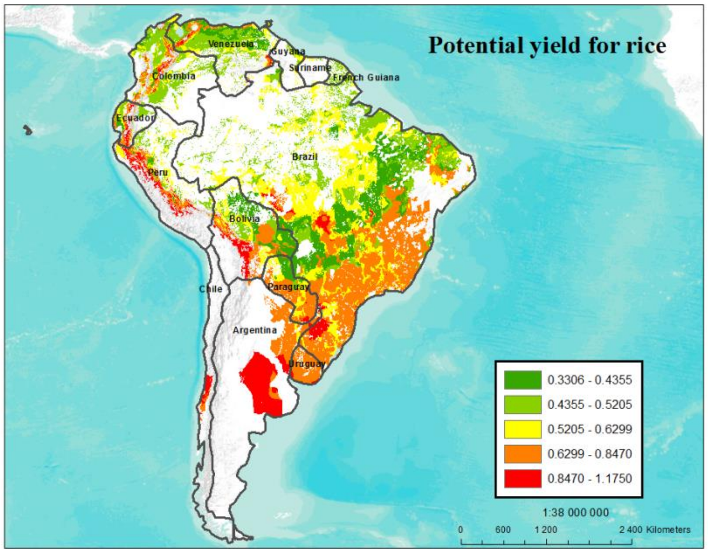


Figure44. Potential yield for rice in South America for year 2000. In kg/m^2. Modified from Monfreda et al. (2008).

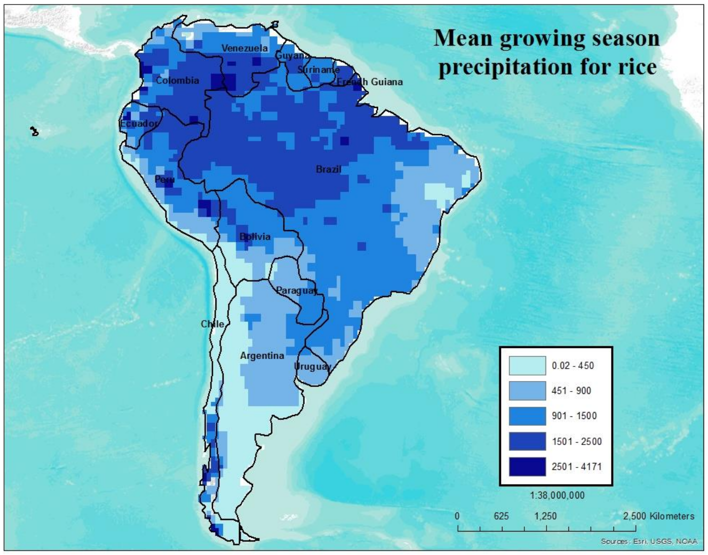


Figure45. Mean growing season precipitation for rice crop for year 2001 in South America. In kg/m^2

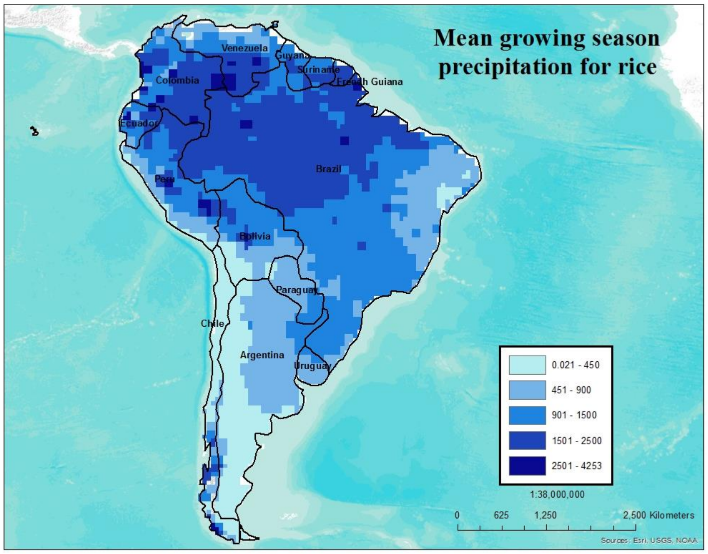
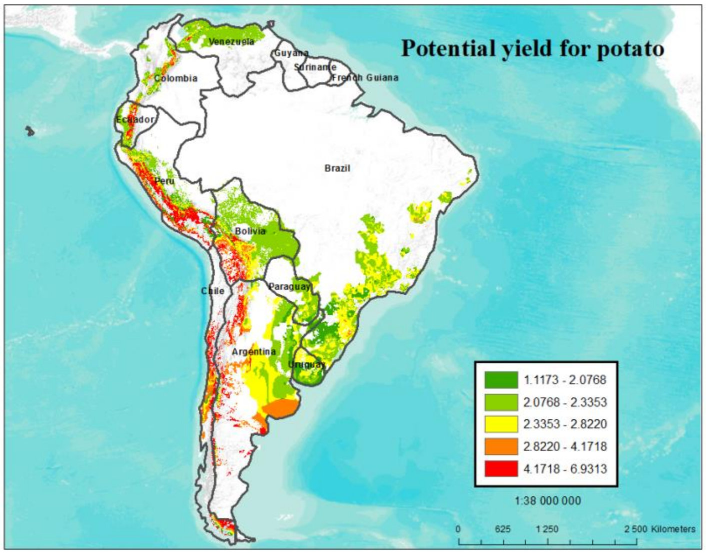


Figure46. Mean growing season precipitation for rice crop for year 2050 in South America. In kg/m^2



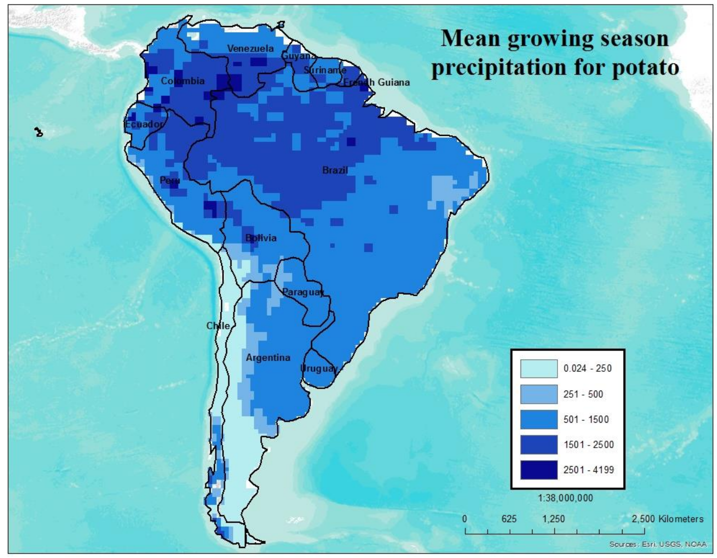


Figure47. Potential yield for potato in South America for year 2000. In kg/m^2. Modified from Monfreda et al. (2008).

Figure48. Mean growing season precipitation for potato crop for year 2001 in South America. In kg/m^2

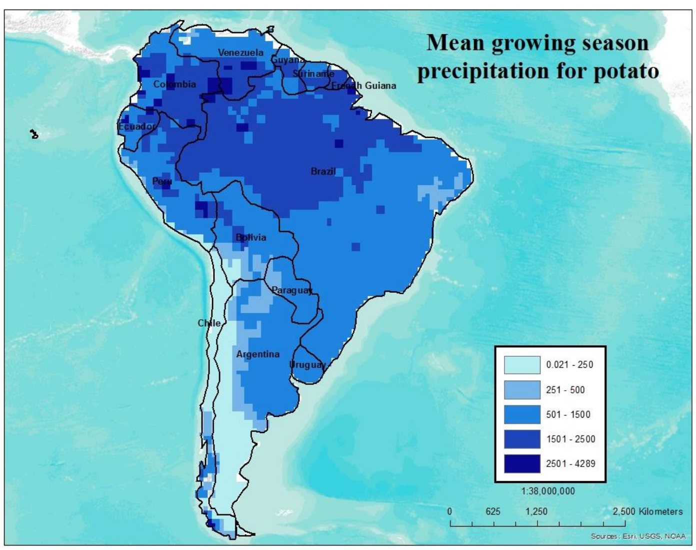


Figure49. Mean growing season precipitation for potato crop for year 2050 in South America. In kg/m^2

Institutionen för naturgeografi och ekosystemvetenskap, Lunds Universitet.

Student examensarbete (Seminarieuppsatser). Uppsatserna finns tillgängliga på institutionens geobibliotek, Sölvegatan 12, 223 62 LUND. Serien startade 1985. Hela listan och själva uppsatserna är även tillgängliga på LUP student papers (www.nateko.lu.se/masterthesis) och via Geobiblioteket (www.geobib.lu.se)

The student thesis reports are available at the Geo-Library, Department of Physical Geography and Ecosystem Science, University of Lund, Sölvegatan 12, S-223 62 Lund, Sweden. Report series started 1985. The complete list and electronic versions are also electronic available at the LUP student papers (www.nateko.lu.se/masterthesis) and through the Geo-library (www.geobib.lu.se)

294 Mattias Spångmyr (2014) Development of an Open-Source Mobile Application for Emergency Data Collection

295 Hammad Javid (2013) Snowmelt and Runoff Assessment of Talas River Basin Using Remote Sensing Approach

296 Kirstine Skov (2014) Spatiotemporal variability in methane emission from an Arctic fen over a growing season – dynamics and driving factors

297 Sandra Persson (2014) Estimating leaf area index from satellite data in deciduous forests of southern Sweden

298 Ludvig Forslund (2014) Using digital repeat photography for monitoring the regrowth of a clear-cut area

299 Julia Jacobsson (2014) The Suitability of Using Landsat TM-5 Images for Estimating Chromophoric Dissolved Organic Matter in Subarctic Lakes

300 Johan Westin (2014) Remote sensing of deforestation along the trans-Amazonian highway

301 Sean Demet (2014) Modeling the evolution of wildfire: an analysis of short term wildfire events and their relationship to meteorological variables

302 Madelene Holmblad (2014). How does urban discharge affect a lake in a recreational area in central Sweden? – A comparison of metals in the sediments of three similar lakes

303 Sohidul Islam (2014) The effect of the freshwater-sea transition on short-term dissolved organic carbon bio-reactivity: the case of Baltic Sea river mouths

304 Mozafar Veysipanah (2014) Polynomial trends of vegetation phenology in Sahelian to equatorial Africa using remotely sensed time series from 1983 to 2005

305 Natalia Kelbus (2014) Is there new particle formation in the marine boundary layer of the North Sea?

306 Zhanzhang Cai (2014) Modelling methane emissions from Arctic tundra wetlands: effects of fractional wetland maps

307 Erica Perming (2014) Paddy and banana cultivation in Sri Lanka - A study

analysing the farmers’ constraints in agriculture with focus on Sooriyawewa D.S. division
308 Nazar Jameel Khalid (2014) Urban Heat Island in Erbil City.
309 Jessica, Ahlgren & Sophie Rudbäck (2014) The development of GIS-usage in developed and undeveloped countries during 2005-2014: Tendencies, problems and limitations
310 Jenny Ahlstrand (2014) En jämförelse av två riskkarteringar av fosforförlust från jordbruksmark – Utförda med Ekologgruppens enkla verktyg och erosionsmodellen USPED
311 William Walker (2014) Planning Green Infrastructure Using Habitat Modelling. A Case Study of the Common Toad in Lomma Municipality
312 Christiana Marie Walcher (2014) Effects of methane and coastal erosion on subsea-permafrost and emissions
313 Anette Fast (2014) Konsekvenser av stigande havsnivå för ett kustsamhälle- en fallstudie av VA systemet i Beddingestrand
314 Maja Jensen (2014) Stubbrytningens klimatpåverkan. En studie av stubbrytningens kortsiktiga effekter på koldioxidbalansen i boreal barrskog
315 Emelie Norhagen (2014) Växters fenologiska svar på ett förändrat klimat - modellering av knoppsprickning för hägg, björk och asp i Skåne
316 Liisi Nõgu (2014) The effects of site preparation on carbon fluxes at two clear-cuts in southern Sweden
317 Julian Will (2014) Development of an automated matching algorithm to assess the quality of the OpenStreetMap road network - A case study in Göteborg, Sweden
318 Niklas Olén (2011) Water drainage from a Swedish waste treatment facility and the expected effect of climate change
319 Wösel Thoresen (2014) Burn the forest - Let it live. Identifying potential areas for controlled forest fires on Gotland using Geographic Information System
320 Jurgen van Tiggelen (2014) Assimilation of satellite data and in-situ data for the improvement of global radiation maps in the Netherlands.
321 Sam Khallaghi (2014) Posidonia Oceanica habitat mapping in shallow coastal waters along Losinj Island, Croatia using Geoeye-1 multispectral imagery.
322 Patrizia Vollmar (2014) The influence of climate and land cover on wildfire patterns in the conterminous United States
323 Marco Giljum (2014) Object-Based Classification of Vegetation at Stordalen Mire near Abisko by using High-Resolution Aerial Imagery
324 Marit Aalrust Ripel (2014) Natural hazards and farmers experience of climate change on highly populated Mount Elgon, Uganda
325 Benjamin Kayatz (2014) Modelling of nitrous oxide emissions from clover grass ley – wheat crop rotations in central eastern Germany - An application of DNDC

326 Maxime Rwaka (2014) An attempt to investigate the impact of 1994 Tutsi Genocide in Rwanda on Landscape using Remote Sensing and GIS analysis
327 Ruibin Xu (2014) Spatial analysis for the distribution of cells in tissue sections
328 Annabelle Finck (2014) Bird biodiversity in relation to forest composition in Sweden
329 Tetiana Svystun (2015) Modeling the potential impact of climate change on the distribution of Western Corn Rootworm in Europe”
330 Joel Forsmoo (2014) The European Corn Borer in Sweden: A Future Perspective Based on a Phenological Model Approach
331 Andrew Ekoka Mwambo (2015) Estimation of Cropland Ecological Footprint within Danish Climate Commissions 2050 Scenarios for Land use and Bioenergy Consumption
332 Anna Lindstein (2015) Land- atmosphere exchange of carbon dioxide in a high Arctic fen: importance of wintertime fluxes
333 Karla Susana Markley Vergara (2015) Present and near future water availability for closing yield gaps in four crops in South America