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The Global Effects of Widespread Adoption of Climate Smart Agriculture

A. De Pinto;

IFPRI, , United States of America

Corresponding author email: A.DePinto@cgiar.org

Abstract:

Climate Smart Agriculture (CSA) is a relatively new approach to agricultural development that aims at increasing productivity in the agricultural sector under changing climate regimes while reducing greenhouse gas (GHG) emissions. We perform an ex-ante assessment of the effects of widespread adoption of CSA by linking spatially-disaggregated data from three different models and focus on three crops, maize, wheat, and rice, which represent about 41% of the global harvested area and 64 % of GHG emissions generated by crop production. The impact of adoption of selected CSA practices is evaluated against a plausible business-as-usual scenario for the period 2010 – 2050 under two climate change scenarios. We find that the highest possible impact of the CSA practices considered is to increase global maize and wheat production by about 4%, and global rice production by 9%. These changes lead to a decrease in the number of people at risk of hunger estimated to be between 23 and 40 million worldwide. Average annual reduction of GHG emissions ranges between 44 and 101 Mt CO2 e. While substantial, this reduction is only 4 – 10% of the estimated global reduction in emissions from the agricultural sector necessary to remain below a 2 °C warming.

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1 Introduction

Most business-as-usual scenarios for farming under changing climate regimes project increasing food shortages by 2050. Underdeveloped economic regions where food security is already problematic and populations are vulnerable to shocks are expected to suffer the worst consequences (Morton, 2007, Rosegrant et al., 2014). Increasing temperatures and frequencies of extreme weather events are expected to undermine the technological and management improvements in crop and livestock productivity (Lobell and Gourdji, 2012). Moreover, climate change is expected to have consequences on a wide range of other ecosystem services (Knight and Harrison, 2012).

Uncertainties in climate change scenarios make it difficult to determine the precise impacts on future agricultural productivity. Warmer temperatures and longer growing seasons may increase agricultural productivity in some high-altitude regions (Rosenzweig et al., 2014), but studies have consistently found that under the most severe scenarios of climate change, significant losses should be expected worldwide (Darwin et al., 1996, 1995; Easterling et al., 2007; Fischer et al., 1993; Fischer and Van Velthuizen, 1996; Nelson et al., 2010; Rosenthal and Kurukulasuriya, 2003; Rosenzweig and Parry, 1994). No matter the severity, regional differences in crop production are expected to grow stronger through time, with the risk of widening the gap between the haves and have-nots and increases in prices and hunger amongst the poorer nations (Nelson et al., 2010; Parry et al., 2004). Moreover, localized weather shocks and emerging pest and disease outbreaks are already compromising stability in crop production, highlighting the urgency for immediate and adaptable management responses (FAO-PAR, 2011).

Perhaps ironically, agricultural production contributes substantially to the problem with yearly greenhouse gas (GHG) emissions that range from 5.0 to 5.8 Gt CO_2 e or about 11% of total anthropogenic GHG emissions, not including land use change (Smith et al., 2014). Combined with forestry and other land uses, anthropogenic land activities contribute about a quarter of annual GHG emissions, the equivalent of 10 to 12 Gt CO_2 e per year three fourths of which are estimated to originate in the developing world (Smith et al., 2014). For example, poor soil management and vast land conversions from tropical forests to poorly productive agricultural systems result in a large climate footprint. Smallholder farming systems contribute to 3.4 percent of the total global emissions (Vermeulen and Wollenberg, 2017).

Considering existing expectations about the future of agricultural production, including smallholder producers in developing countries – the sustainable development goal (SDG) 2.3 calls for “double[ing] agricultural productivity and incomes of small-scale food producers by 2030” (United Nations General Assemby, 2015) – it is undisputed that farmers need options to sustainably increase production under a changing climate and ideally reduce emissions.

Climate Smart Agriculture (CSA) proposes an approach that jointly addresses these problems by combining the concepts of sustainable production, resilience and climate change adaptation and mitigation. It was introduced first in 2009 (FAO, 2009a, 2009b) and more widely a year later at the First Global Conference on Agriculture, Food Security and Climate Change (FAO, 2010). CSA is a framework that supports decisions addressing climate-related risks to agricultural production systems and societal wellbeing by considering three foundational outcomes and by fully accounting for the trade-offs and synergies among them (Rosenstock et al., 2016). It is comprised of agricultural systems that contribute to, or at least consider, three outcomes, the three pillars of CSA: 1) sustainable and equitable increases in agricultural productivity and incomes, 2) greater resilience of food systems and farming livelihoods, and 3) reduction and/or removal of greenhouse gas emissions associated with agriculture, where possible.

Synergies between productivity, adaptation, and mitigation in the agriculture sector appear to be possible (Smith and Olesen, 2017), but they are not automatic, and reduction of emissions in particular needs to be promoted and enforced. It follows that the conditions for adoption are highly context- and location-specific which highlights the need for information and data to make the approach operational (Mccarthy et al., 2011)..

A significant amount of the literature has focused on the agronomic aspects of CSA, its economic benefits to farmers and the barriers to its adoption, to our knowledge, no study has analyzed the global effects of widespread adoption of CSA. This is precisely the goal of this study. We perform an ex-ante assessment of the effects of widescale adoption of CSA practices and technologies to evaluate the potential effects on multiple metrics relevant to agricultural development and food security. While we can only make tentative statements about how resilience is affected given that despite being one of the foundational concepts, resilience is still defined with analytical and operational imprecision (Levine, 2014; Watts, 2014), this study clearly indicates some of the important benefits and limits of the CSA approach.

2 Methods and Data

The spatially-disaggregated data of three models were linked to carry out the ex-ante assessment of the effects of widescale adoption of CSA practices and technologies: the Spatial Production Allocation Model (SPAM) (You et al., 2006), Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al., 2003), and the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT v3.3, Robinson et al., 2015). The modeling develops as follows: the SPAM model is used to identify the location of crop production and the soil and weather conditions in which production takes place. Once crop production is geographically located, the DSSAT crop model evaluates yields with current agricultural practices and yields with alternative management practices. Yield changes are used in the IMPACT model to compute global changes in prices and ensuing effects on production and food security metrics for the period 2010–2050. Three widely grown crops, maize (*Zea mays*), wheat (*Triticum aestivum*), and rice (*Oryza sativa*), were selected for the analysis, considering the facts that together they represent about 41% of the global harvested area and per the calculations of Carlson et al. (2016) approximately 64 % of GHG emissions generated by crop production globally. The effects of the adoption of CSA practices on production are compared with the outcomes of a business-as-usual (BAU) scenario in which assumptions regarding GDP, population and agricultural productivity growth are made[1] but in which climate-smart practices are not adopted.

The SPAM model uses crop suitability assessments, information regarding population density, and any other available prior knowledge regarding the geographical distribution of specific crops or crop systems to spatially allocate sub-national statistics of crop production and cropland data (period 2004-2006) to either 5-arc-minute or into 0.5-degree grid-cells. We used this model to geographically locate the area allocated to the three crops considered. For each 0.5-degree SPAM grid-cell (a square of approximate size of 56 km by 56 km at the equator), a database cataloging the dominant management practices the input used (i.e. varieties employed, application rates of inorganic fertilizers, organic amendment

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[1] These assumptions are constant across all the scenarios considered.

availability, and water management practices) was assembled. High-resolution data about climate scenarios, irrigation type, and soil properties were also cross-referenced for each grid-cell. These data layers are essential to run simulations in DSSAT where crop growth and yields are modeled as a function of the interaction between biophysical elements of the crop systems (e.g. soil, weather, and crop) and management practices (e.g. tillage, nutrient application, and water availability) on global scale. After model calibration, simulations for the BAU and the scenarios that simulate the adoption of CSA practices were executed on global scale over the period 2010 - 2050.

The yield responses calculated using DSSAT are used as input for the simulations implemented in the IMPACT model (Islam et al., 2016; Robinson et al., 2015; Rosegrant et al., 2014). IMPACT is a partial equilibrium multi-market model of the agricultural sector that models the behavior of a global competitive agricultural market and simulates supply, demand, and prices for agricultural commodities at country level. The model has a broad record of applications ranging from assessing the potential effects of climate change on global food production and nutrition (Springmann et al., 2016) to evaluating the global effects of biofuel production (Rosegrant, 2008) to country-level assessments of low-emission development strategies (De Pinto et al., 2016). The yield changes evaluated in DSSAT act as shifters for the crop-specific supply curves and also affect the yield growth rates in the IMPACT environment.

Together with yield responses associated with adoption of CSA practices, spatial and temporal changes in soil carbon stocks and direct nitrous oxide (N_2O) emissions were simulated in soil organic matter (SOM) modules embedded into DSSAT. For rice production systems, methane (CH_4) emissions from rice fields were calculated by combining DSSAT-simulated rice biomass with IPCC Tier 1 method’s emission coefficients proposed by Yan et al. (2009). Finally, all GHG emissions were converted into tons of CO_2 e by using global warming potential for 100-yr time horizon of each GHG (IPCC AR5) and then were combined with IMPACT projected areas to estimate the impacts of CSA adoption on GHG emissions.

3 Simulation scenarios

We evaluated the impact of the CSA practices and technologies by comparing scenarios in which these practices are adopted against a plausible BAU scenario that assumes that current practices are retained by all farmers. All scenarios assume that agriculture is developing under climate change conditions. Simulations in DSSAT and IMPACT adopt climate change scenarios derived from the work of the Intergovernmental Panel on Climate Change 5th Assessment Report (IPCC AR5). Climate change projections are generated by using two global circulation models (GCMs): GFDL-ESM2M (Dunne et al.,

2012) and HadGEM2-ES (Jones et al., 2011), under a Representative Concentration Pathway (RCP) of 8.5 (Meinshausen et al., 2011). The GFDL climate change scenario can be considered as drier and cooler compared to HadGEM[2].

3.1 Business-as-usual scenario

The BAU scenario reflects the use of current practices and technologies throughout the simulated period of 2010 –2050. This scenario includes information on representative cultivar, planting density, planting and harvesting dates, tillage practice, irrigation schemes, residue harvest rate based on national statistics databases, literature reviews, and consultation with experts. Simulated yields do change over time due to changes in soil fertility and interactions between the crop system and climate conditions.

The IMPACT BAU scenario uses projected yield changes generated by the crops model but it also includes gradual improvement in crop yields resulting from estimated advances in technology and investments in the agriculture sector. Yield changes also reflect variations in water distribution and availability, as well as shifts in supply and demand (such as those caused by population and economic growth), with its consequent changes in global food trade. Population and countries' GDP growth is also factored in IMPACT simulations[3]. The IMPACT economic model uses trends in population and income growth obtained using the Shared-Socioeconomic Pathway 2 scenario (SSP2), a middle-of-the-road projection developed for the IPCC AR5 (O'Neill et al., 2014).

3.1.1 Calibration of the crop model

The results of this study are highly sensitive to how accurately DSSAT can represent yields and emissions at both the grid-cell and regional level. Therefore, we performed an extensive calibration of DSSAT results to ensure that the simulated yields in the reference years represent as accurately as possible national statistics data. After this calibration, simulated yields for maize and wheat are comparable to FAO yields with very good fits, R^2 0.87 and 0.75 respectively; the fit is lower but still acceptable for rice, R^2 0.63.

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[2] This study considers only changing trends in average temperature and precipitation. We acknowledge that the magnitude and severity of impacts from extreme events, sea level rise, changing patterns of pests and diseases are likely to be significant, but they are beyond the scope of the present analysis.

[3] Detailed information regarding the assumptions underlying the BAU scenario in IMPACT are available in (Robinson et al. 2015).

It must be noted that only monoculture systems were simulated and we acknowledge that this is a very stylized representation of reality. This limitation should be addressed in future research with the inclusion of intercropping and rotation schemes.

3.2 Climate-smart alternatives

There appears to be a certain consensus about the suitability of a group of specific practices to deliver across the objectives of climate-smart agriculture. Four practices and technologies were identified and used in the simulations. These practices are generally thought to have the potential to be adopted widely and they are already utilized and tested in some areas. The technologies considered for maize and wheat are no-till and integrated soil fertility management, while those for rice are alternate wetting and drying (AWD) and urea deep placement (Table 1).

Table 1: CSA technologies considered in this study.

CSA technology	Definition	Crop	Potential effects on yields and GHG emissions	Reference
No tillage	minimum or no soil disturbance, often in combination with residue retention, crop rotation, and use of cover crops	Maize, wheat	• Positive or neutral • Uncertain effect on GHG emissions	• (Erenstein et al., 2012, 2008; Hobbs et al., 2008; Pittelkow et al., 2015) • (Powlson et al., 2014)
Integrated soil fertility management	combination of chemical fertilizers, crop residues, and manure/compost	Maize, wheat	• Positive effects on yields • Variable effects on GHG emissions	• (Agegnehu et al., 2014; Chivenge et al., 2011; Vanlauwe et al., 2011) • (Gentile et al., 2008)
Alternate wetting and drying	repeated interruptions of flooding during the season, causing the water to decline as the upper soil layer dries out before subsequent re-flooding	Rice	• Lower to no significant changes in yields. • High confidence in lower GHG emissions due to reduction of methane emissions	• (Devkota et al., 2013; Huda et al., 2016; Rejesus et al., 2010) • (Pandey et al., 2014; Tyagi et al., 2010)
Urea deep placement	strategic burial of urea ‘supergranules’ near the root zones of crop plants	Rice	• Positive results on yields • Reduction of GHG emissions	• (Bandaogo et al., 2015; Huda et al., 2016) • (Gaihre et al., 2015)

3.2.1 Adoption of alternative technologies

Alternatives to the BAU were constructed by assuming that farmers who are currently using a particular set of practices to produce either maize, wheat, or rice are offered a portfolio of alternatives from which to choose (i.e. the four CSA practices considered). Two adoption rules are used to generate the alternative scenarios. The first one assumes that the prerequisite for adoption is that the alternative technology or practice must return a yield gain compared to the BAU and that farmers choose the technology that generates the highest gain[4]. The second adoption rule also requires that alternatives generate higher yields than current practices but farmers choose the one that decreases emission intensity the most[5]. If none of the alternatives increase yields, farmers retain their current practices.

It is well known that adoption of alternatives to the status-quo depends on many other factors other than yields. There is extensive literature that investigates the socioeconomic determinants of adoption of alternative practices and accounts for characteristics of farmers and households, farmers' access to markets and to credit, the characteristics of a particular technology, the quality of extension services, and potential risk factors (Bewket, 2007; Enfors and Gordon, 2008; Shiferaw et al., 2009; Teklewold and Kohlin, 2011). Furthermore, it is possible for a farmer to adopt a new technology that reduces yields if the costs of production are reduced more than proportionally. While these considerations are important and are particularly relevant at the farm-level, it is difficult to imagine that countries would favor the widespread use of technologies that reduce yields given the pressure of population growth and changing diets. The yield-increase assumption, albeit greatly simplifying, is therefore considered to be justified. We also assume that when an alternative is yield-superior to the status quo in a particular grid-cell, *all* farmers in that area adopt the best alternative from the first year. This assumption departs significantly from previous studies (e.g. Rosegrant et al., 2014) in which adoption is dependent on other socio-economic factors and has a ceiling (usually lower that 100%) which is reached after a certain number of years. Results of this analysis should therefore be interpreted as representing an upper bound of the changes induced by the widespread adoption of CSA practices.

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[4] Due to the scale at which the analysis is carried out, each grid-cell is treated as an individual farm and it is assumed that it can properly represent as many farms as are actually contained in the grid-cell area.

[5] There are connections between reduction of emission intensity, efficient use of energy and total-factor productivity (Ayres et al., 2002). These links should be explored further but they are not the target of this analysis. Adoption of CSA practices that reduce emission intensity could be due to policies that target GHG emission reduction or more general ones that aim at increasing total-factor productivity.

4 Results

4.1 Business-as-usual scenario

According to the IMPACT simulations during the period 2010 – 2050 (Figure 1), production of the main cereals maize, wheat, and rice is expected to increase by 36 – 58%, 40 - 44%, and 18 - 20%, respectively depending on the particular climate scenario used. Their prices are projected to increase by 56 - 103%, 24 - 46%, and 44 - 60%. Combined with economic growth and changing diets, these changes are expected to affect hunger and nutrition lowering the number of undernourished children by 30 - 33% and reducing the population at risk of hunger by 43 - 52% globally.

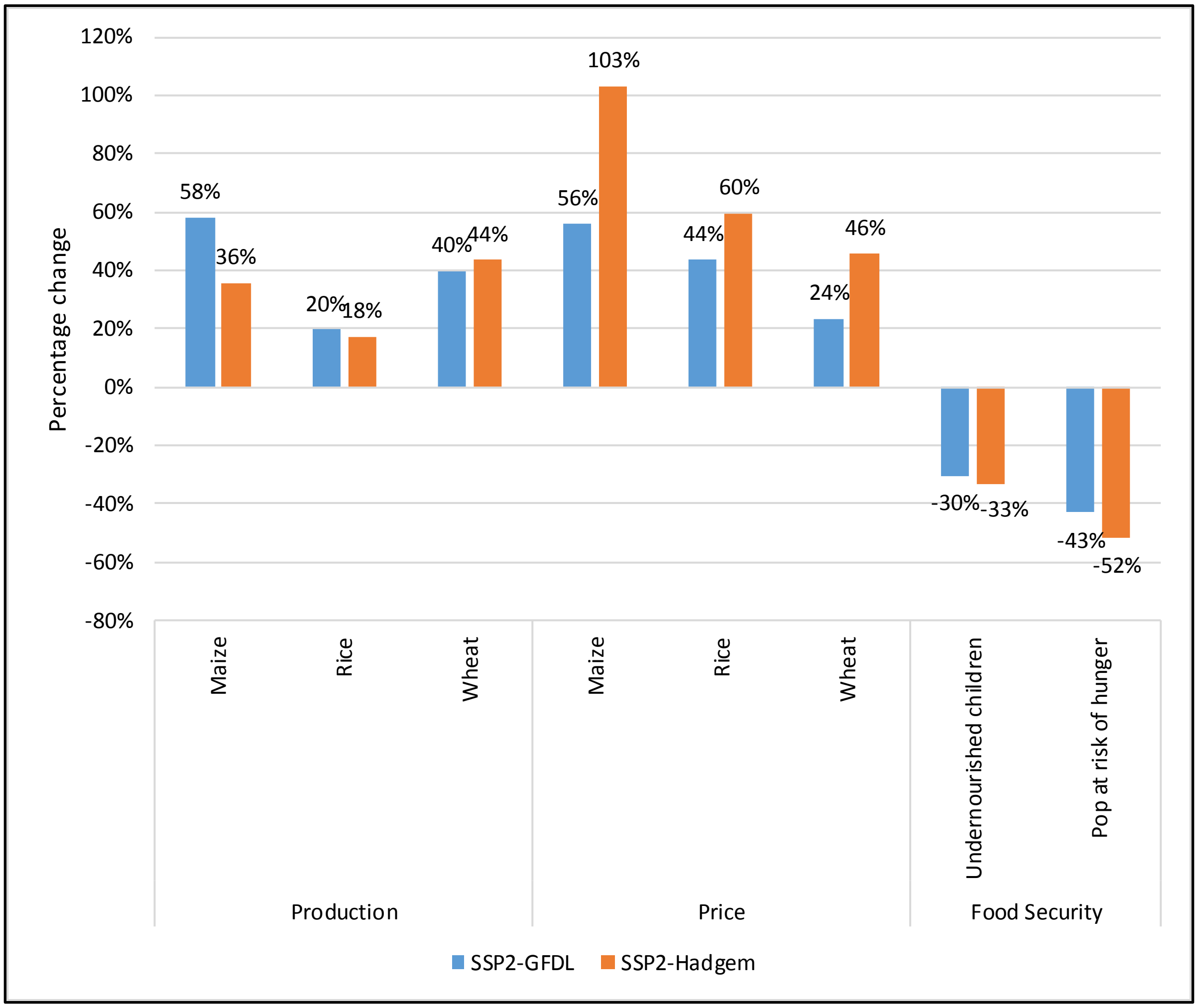

Figure 1: Changes in production, prices, undernourished children, and population at risk of hunger. Period 2010 – 2050

4.2 CSA adoption scenarios

Results for the scenarios that simulate global adoption of CSA practices and technologies indicate that their effects on productivity and total production are sufficient to affect global markets.

The effects on total production and subsequently on prices are dependent on how widely CSA practices and technologies are adopted. The adoption rates for the two scenarios are shown in Table 2.

Table 2: Adoption rate by crop under the different climate and alternative scenarios

Scenario	Adoption rate of alternative practice Maize (GFDL – HADGEM)	Adoption rate of alternative practice Wheat (GFDL – HADGEM)	Adoption rate of alternative practice Rice (GFDL – HADGEM)
Adoption of CSA practices dependent on increased yields	70.2 %– 72.9%	73.9% – 75.3%	51.0% – 55.9%
Adoption of CSA practices dependent on reduction of emission intensity *and* increased yields	37.8% – 38.8%	45.0% – 47.8%	42.8% – 47.3%

As expected, adoption is lower when the two conditions of reduction of emission intensity and increase in yields are satisfied. Adoption seems to decrease more for maize and wheat than for rice indicating that for these crops the considered practices do not automatically lead to a reduction of emissions. By 2050, CSA practices are adopted on a total of approximately 372 million hectares in the first scenario (top row) and 241 million hectares in the second (bottom row).

CSA technologies are estimated to increase production of maize between 3 and 4% and wheat production by between 2 and 4% compared to the BAU scenario. CSA practices and technologies appear to have the largest effect on rice, for which production is approximately 9% percent larger than production with the BAU practices (Figure 2).

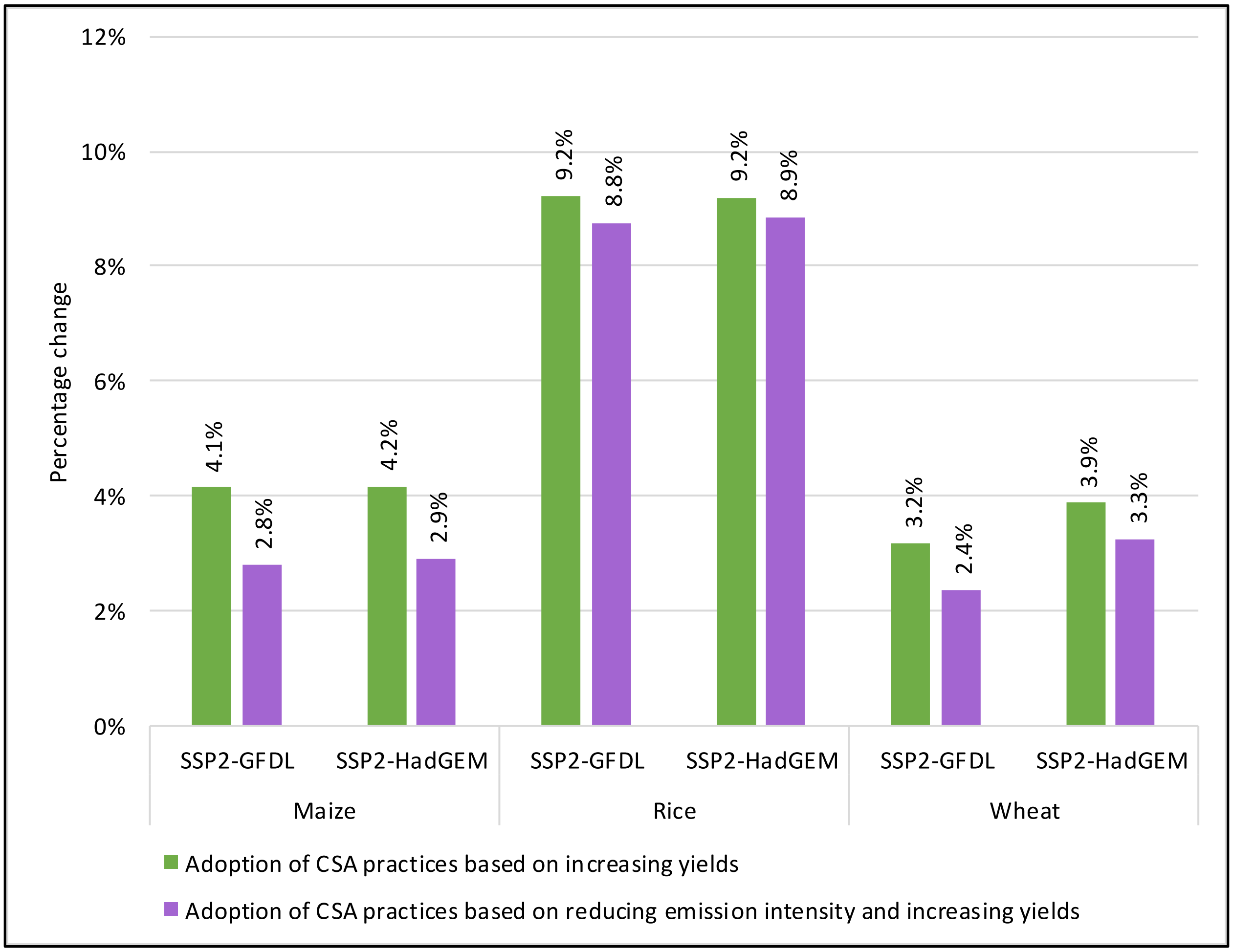

Figure 2: Percent change in production (total output) – CSA adoption scenarios compared to business-as-usual.

The adoption of CSA technologies causes an increase in production sufficient to have a sizable effect on the world price of maize, rice and wheat (Table 3). Prices for these commodities are still projected to increase but the increase in supply caused by CSA practices reduce prices growth compared to BAU.

The combination of higher production and lower prices reduces producers' incentives to expand production as the demand for wheat and rice can be satisfied with less harvested area. Harvested rice area is projected to decrease by approximately 5% across all scenarios and climate models and harvested wheat area will decrease between 1 and 2.4%. Harvested area for maize is projected to increase by 0.1 – 1.1% depending on the climate model considered. The net effect of these changes is a decrease in harvested areas estimated to be between 8 million and 13 million hectares. Even though harvested area is not equivalent to physical area, and this is particularly true for rice, this result is suggestive of a reduced pressure on forests and other natural areas that might be environmentally significant and rich in carbon.

Table 3: Percent change in 2050 world prices compared to business-as-usual

Scenario	**Maize (GFDL / HADGEM)**	**Wheat (GFDL / HADGEM)**	**Rice (GFDL / HADGEM)**
Adoption of CSA practices dependent on increased yields	-7.7% / -8.8%	-9.1% / -12.3%	-27.1% / -27.5%
Adoption of CSA practices dependent on reduction of emission intensity and increased yields	-5.3% / -6.3%	-6.6% / -9.6%	-25.8% / -26.4%

Under the scenario that considers adoption of CSA technologies based on yield increases, the population at risk of hunger decreases by 6.3 – 8.4% by 2050 compared to the business as usual, depending on the climate scenario considered. This is equivalent to 27 to 40 million fewer people at risk of hunger. Results do not change greatly for the second scenario in which adoption is dependent on the reduction of emission intensity and increasing yields: 23 to 36 million fewer people at risk of hunger. The decrease in undernourished children is low under both adoption scenarios and ranges between 1.9 to 2.4% (in the order of 2,000,000 children).

Overall, the considered CSA practices also appear to be beneficial for soil fertility, sustainability, and potentially to resilience in general. The soil organic carbon concentration, which not only increases fertility but also soil water retention, is estimated to grow on average by approximately 0.06 t ha^{-1} yr^{-1} over the area that adopts the alternative practices for the scenario based on yield increases and by approximately 0.13 t ha^{-1} yr^{-1} when adoption is based on reducing emission intensity and yield increases. The reported increases in soil organic carbon are changes with respect to the BAU scenario and therefore should be interpreted mostly as avoided soil carbon losses rather than actual gains from the initial conditions.

There are some important distinctions between the two scenarios as far as GHG emissions are concerned. When choice is only based on yields, the cumulative reduction in GHG emissions between 2010 and 2050 is estimated to be equivalent to 38 – 50 Mt yr^{-1} CO_2 e depending on which climate scenario is used. Yearly reduction of emissions increases significantly when reduction of emission intensity is one of the criteria of adoption. The reduction in GHG emissions is estimated to be equivalent to 99 – 103 Mt yr^{-1} CO_2 e, depending on the climate scenario.

Wollenberg et al. (2016) calculated that in order to meet the challenge of staying below a 2 C° warming, the agricultural sector should reduce GHG emissions by about 1 Gt CO_2e per year. The results of this analysis indicate that adoption of CSA practices and technologies could contribute to 5% of this reduction if CSA is offered as an option to farmers and they make their decision based on yield increases and to 10% if there are in place the proper incentives that promote reduction of emission intensity.

4.3 Sensitivity analysis

The sensitivity of the results to the underlying assumptions on adoption of the alternative practices was explored using varying rates of adoption and alternative decision rules that expand on the two scenarios already presented. The adoption rates used by Rosegrant et al. (2014) that introduce a socioeconomic dimension to adoption were utilized. Rosegrant et al. impose a limit to adoption based on expert opinion and on criteria that reflect key characteristics of a technology. The upper bound imposed effectively reduces the number of hectares that potentially transition to the alternative practices (Table 4). For instance, if there were one hundred hectares on which no-till returns higher yields than current practices, only seventy hectares would actually be considered as adopting no-till in the simulation.

Table 4: Assumed maximum level of adoption by technology

CSA technology	**Adoption ceiling (%)**[a]
No tillage (NT)	70
Integrated soil fertility management (ISFM)	40
Alternative wetting and drying (AWD)	40
Urea deep placement (UDP)	40

[a] From Rosegrant et al. (2014).

Additionally, even though it is often the case that farmers do not pay the full cost of the water used for irrigation (Cornish et al., 2004; Easter and Liu, 2005), a scenario in which the potential reduction in production cost resulting from AWD adoption was simulated. Irrigation costs represent from 3 to 36% of production costs (Farooq et al., 1999; Klonsky et al., 2012; Perret et al., 2013) and AWD is reported to reduce irrigation cost up to 30% (Kürschner et al., 2010; Lampayan, 2012). Based on this information, it is assumed that the adoption of AWD can reduce production costs up to 9%. Once the reduction in production costs are accounted for, AWD does not have to induce an increase in yields to be adopted. As a result of accounting for the reduction in production costs, AWD is adopted on some 800,000 additional hectares compared to the other scenarios.

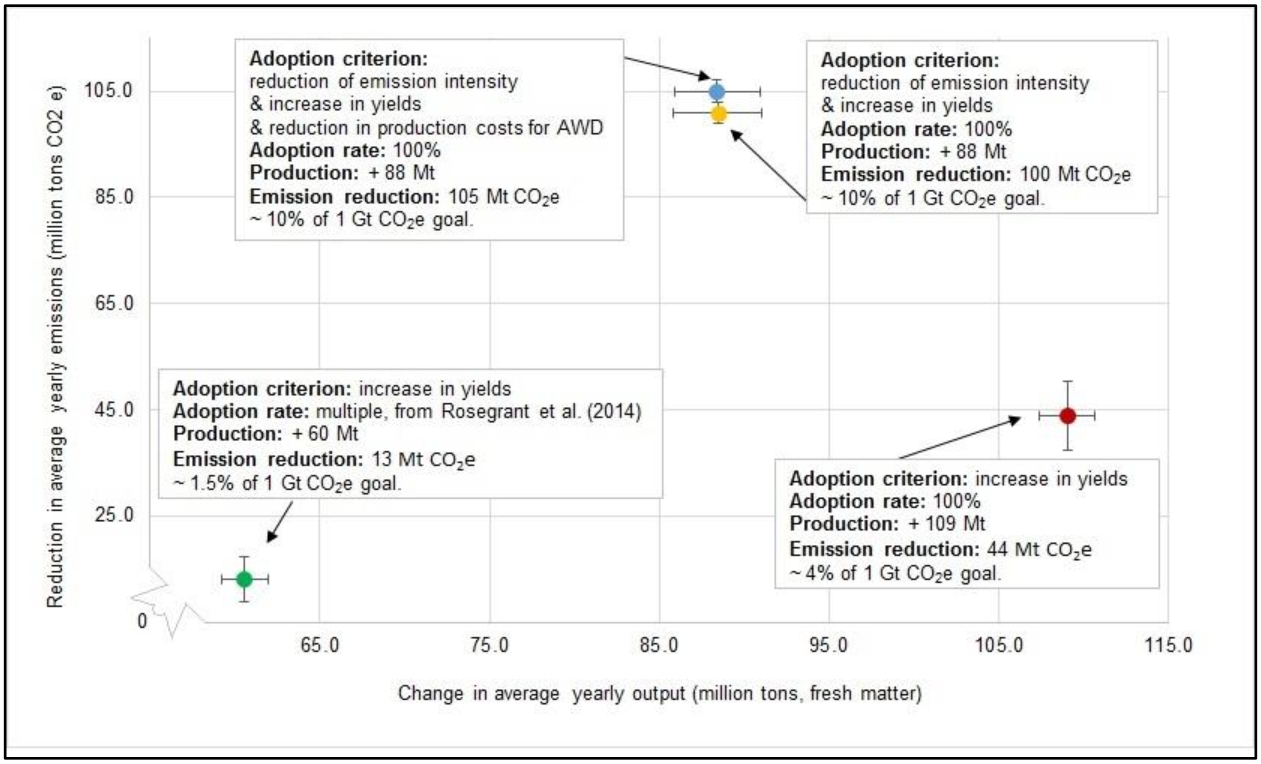

Figure 3: Changes in average yearly output and GHG emissions for alternative scenarios

Figure 3 provides a summary of the results for a selection of simulated scenarios with different adoption assumptions. The change in total output is computed using the cumulative fresh weight for the three crops and reported as a yearly average for the period considered. The change in GHG emissions are computed as the yearly average for period 2010 – 2050. The whisker bars indicate the spread of results across the two climate scenarios. The average of the two estimates is indicated by the colored marker. Several messages can be drawn from these results.

Increased production and reductions in emissions are strongly dependent on adoption rates. When the simulation uses adoption rates lower than 100% (arguably more plausible – green marker), the gains in output and the emission reduction decrease substantially. Globally, yearly output for the three crops increases on average by 60 Mt (approximately 3.3% of world's output for maize, wheat and rice) and GHG yearly emissions are reduced on average by 13 Mt CO$_2$e. These changes are still noteworthy insofar that they show that increasing productivity and reducing GHG emission is possible. The reduction in emissions is rather small and represents only about 1% of the 1 Gt CO$_2$e goal calculated as the reduction in emission from the agricultural sector necessary to stay below the 2 °C global warming threshold

(Wollenberg et al., 2016). Clearly, lower adoption rates than the ones used following Rosegrant et al. would lead to even lower changes in both output and emission reduction.

The emphasis on reducing emission intensity is essential to increase total GHG emission reductions. Compared to BAU, yearly average emissions are reduced by 101 Mt CO_2e (yellow marker) when the adoption of the CSA practices is predicated on reducing emission intensity and only by 44 Mt CO_2e when the only requirement for adoption is a gain in yields (red marker). This represents more than a doubling in emission reduction and brings the contribution to the 1 Gt CO_2e reduction from the agricultural sector from 4% to 10%.

Tradeoffs between increasing productivity and reducing GHG emissions are clearly present. When adoption of CSA practices is based on increasing yields, total output for maize, wheat and rice increases by approximately 109 Mt per year (red marker). This is equivalent to an increase in the world output for these three crops of about 5.9%. If the emphasis shifts onto reducing emission intensity, the total gain in output is 88 Mt, a 4.8% increase in the world output (yellow marker). These results indicate that there is a substantial amount of area in which CSA practices can increase yields but not necessarily reduce GHG emissions. This is consistent with field findings which indicate that CSA practices do not reduce emissions in all conditions and require careful tailoring to the particular local soil and weather conditions.

Finally, practices that are particularly suited to reducing emissions such as AWD can provide an additional measure of emission reduction. When the full benefits of adopting AWD are accounted for (i.e. reduction in production costs), yearly average emission reductions are the highest: between 103 Mt yr^{-1} CO_2e and 107 Mt yr^{-1} CO_2 e (blue marker). It is important however to point out how gains in productivity are reduced by about 20% when the reduction of GHG emissions becomes the determinant of adoption choices.

5 Discussion and Conclusion

There is a growing body of literature that analyzes the effects of CSA in terms of agronomic, economic and environmental benefits. Many of these studies focus on the benefits at the farm and household levels. This study takes a broader geographical perspective and attempts an ex-ante assessment of the global effects of widespread adoption of climate-smart agricultural practices and technologies for the production of three cereals: maize, wheat and rice. While only three crops are considered, they are important staple crops across the globe and represent about 41% of the global harvested area and approximately 64 % of GHG emissions generated by crop production globally. Household-level analyses are important to determine, among other things, the viability of new practices and their benefits for households' wellbeing. However, a broader outlook provides insights into wide-ranging issues related to changes in prices, accessibility to food products, and the cumulative effects on GHG emissions.

The first set of results reported, which represents an upper-bound effect of widespread adoption, indicates that CSA practices can positively affect yields and production, induce a reduction in prices, and can decrease the number of people at risk of hunger and the number of undernourished children. These changes can also reduce the pressure for cropland expansion and induce an increase in soil organic carbon content, or at least reduce soil organic carbon losses, indicating that productivity can be increased in a more sustainable manner than with the current practices. Taken together, these results are suggestive of an increase in resilience to climate change. However, not knowing how these changes affect many other important dimensions of resilience such as the nutritional quality of people's diets, the accumulation of assets, the conditions of landless laborers, female workers and tenant farmers, it is impossible to evaluate the impact of CSA practices on resilience.

Results also show that it is possible to reduce GHG emissions while increasing productivity on a global level. The reduction in emissions is dependent on how much emission intensity can be factored in farmers' decision to adopt CSA practices. The abatement of GHG can reach approximately 100 million Mt of CO_2e per year, or about 10% of the 1 Gt CO_2e goal indicated as the necessary contribution in reduction of emission from the agricultural sector to remain below the 2 °C global warming threshold (Wollenberg et al., 2016). There are some additional indirect effects on cattle that might reduce these benefits. These relationships should be the target of additional research.

However, there are clear tradeoffs between increasing total output and reducing GHG emissions because many of the CSA practices do not necessarily reduce emissions and increase yields in all conditions. Simulations in which the adoption of alternative practices requires that emission intensity are reduced in conjunction with an increase in yields provide an indication for these tradeoffs. Total production is reduced by about 20% while the reduction in GHG emissions more than doubles. Resolving these tradeoffs in an economically efficient manner depends on a correct pricing of the factors of production and possibly on the existence of a price for carbon. Given the multi-objective nature of the approach, and the fact that the performance of CSA practices is highly context specific, offering farmers a portfolio of options from which to choose and educate them about their benefits does not automatically lead to meeting the goals of CSA. This is particularly true if meaningful levels of reductions in GHG must be achieved.

The overall positive outcomes are strongly dependent on the assumed uptake of CSA practices by farmers. A second set of results based on simulations that use lower and more plausible adoption rates (Rosegrant et al. 2014), show that the influence of CSA practices on global markets and their reduction of GHG emissions becomes increasingly marginal. This points to the importance of finding and promoting solutions to long-standing problems that are not resolved by the CSA approach. These are the necessity of well-functioning extension services, the amount and quality of the information provided to farmers, and the removal of a host of other barriers that prevent adoption of new and beneficial technologies and practices. Some policies such as correct pricing of inputs like water, which provides an incentive for the adoption of AWD practices, could be easier to pursue in certain conditions than persuade farmers to pay attention to the GHG emissions deriving from their activities. A compensation for emission reductions, a carbon price, would also provide farmers with sufficient incentives to include GHG emissions in their production choices.

The insights offered by the results of this analysis point to the importance of staying true to the original broad intent of CSA and not to reduce it to a list of acceptable practices and actions. Wheeler and von Braun (2013) have suggested that the whole food system needs to adjust to climate change (i.e. trade, stocks, nutrition and social policies) and Frelat et al. (2016) have suggested that targeting poverty through improving market access and off-farm opportunities is a better strategy to increase food security than focusing on agricultural production and closing yield gaps. These authors make important calls for approaches that are much broader than a narrow, albeit important, focus on increasing yields and this can be applied to CSA as well. CSA should be used as a framework for decision-making ranging from the farm to the policy level. A set of guiding principles to identify technologies and practices, tools and policies by concurrently considering the three pillars of CSA and their trade-offs. CSA, with its multi-objective approach, has the potential to induce productive conversations and negotiations among ministries which often do not share or coordinate objectives. The wide repertoire of technologies and practices that have already been explored and are known for their potential to deliver in some of domains relevant to CSA should be deployed. For example, a considerable amount of knowledge has already been accumulated in studying conservation agriculture and sustainable land management and this can inform and become an integral component of CSA. Furthermore, assuring that CSA considers the interactions of agricultural land with carbon-rich environments e.g. forests and mangroves), and that includes agroforestry, crop-livestock and silvopastoral systems as potentially important elements of climate-smart agricultural development can elevate the role of CSA in addressing poverty and food security in a changing climate.

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