65% of Maize, 49% of Rice and 35% of Wheat Harvest Globally can be explained by

- Human Development Index (HDI)
- Gross Domestic Products (GDP) per capita
- Income Distribution (GINI Index)
- Fertilizer Use Intensity (kg/ha)
FOOD SCIENCE & TECHNOLOGY | RESEARCH ARTICLE

Strategies to boost global food production: Modelling socioeconomic policy scenarios

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Abstract: Current research on food security is dominated by crop, climate and demographic modellers who project how changes in weather and population may affect the global demand and supply of food. But socioeconomic factors also play a crucial role in determining the amount of food we produce. In this paper, we present spatially explicit multiple regression models that demonstrate 65% of maize, 49% of rice and 35% of wheat harvests (globally) can be explained by four socioeconomic variables: income distribution, gross domestic product/capita, human development index and fertilizer use. Using these insights, we model the effect that different hypothetical policy scenarios may have on boosting yields and demonstrate that it could be possible to increase global cereal harvests by 70%. This research demonstrates that to understand threats to global food security, and develop strategies to avert problems, scientists must integrate socio-economic data with biological and demographic factors if they want to provide comprehensive advice to policy makers.

Subjects: Environment & Agriculture; Earth Sciences; Food Science & Technology

Keywords: crop yield; yield gap; food security; socioeconomic policy scenarios; spatial differentiation; spatially explicit model

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Reducing yield gap, eliminating food waste, and diversifying food consumption can be potential solutions to food insecurity problem. This paper presents a possibility of feeding growing human population in future by reducing the yield gap of three major staple crops across the world through the improvement of socioeconomic conditions.

PUBLIC INTEREST STATEMENT

Producing enough food for the growing human population is a major global challenge. One of the solutions to this problem is to focus on boosting food production in regions that have not reached their full agricultural potential. Socioeconomic factors, amongst others, play a crucial role in determining the amount of food we produce. This paper explores the key socioeconomic factors that explain global food production and demonstrated that about 65% of maize, 46% of rice and 35% of wheat harvests (globally) can be explained by four socioeconomic variables: income distribution, gross domestic product per capita, human development index and fertilizer use. Based on this relation, the paper further demonstrated that there is a possibility of increasing global cereal harvests by 70% if conditions of all four variables in all countries were to be developed to the 95% level of the best country within each economic region.
1. Introduction and literature

Thanks to global population growth, as well as urbanization and rising affluence, there is a growing demand for food (Lutz & KC, 2010; Satterthwaite, McGranahan, & Tacoli, 2010). This leads some to conclude that global food security is threatened unless production increases by as much as 70% by 2050 (Bruinsma, 2009; Godfray, Beddington et al., 2010; Godfray, Crute et al., 2010). At the same time, recent work suggests that crop yields will not be sufficient to meet demand (Ray, Mueller, West, & Foley, 2013) and many worry that climate change is likely to cause declines in food production over the next century (Jaggard, Qi, & Ober, 2010; Royal Society, 2008; Sitch et al., 2008). When evaluating all these challenges together, many argue that new technologies (Brown & Funk, 2008) including highly productive genetically modified organisms (Fedoroff, 2013) must be developed to ensure food security over the next generation (Paarlberg, 2010). However, this is extremely controversial, and many others believe that such “high-tech” solutions threaten biodiversity (Tirado & Johnston, 2010) and lead to pesticide resistance (Duke & Powles, 2009) compounding many of the problems associated with today's capital intensive modern food system (e.g. see Fraser et al., 2016; KC, Fraser, Pascoal, Dias, Zundel, 2016; KC, Haque, Legwegoh, Fraser, 2016; Waltz, 2009).

Given the controversy over biotechnologies and genetically modified crops, it is important to investigate non-technical solutions to the challenge of feeding nine billion people. One area which has recently been explored is the amount of food waste. Recent reports on the subject suggest that worldwide about one third of the food we produce is never consumed (Gustavsson, Cederberg, Sonesson, van Otterdijk, & Meybeck, 2011; Hall, Guo, Dore, & Chow, 2009; Institute of Mechanical Engineers, 2013; Parfitt, Barthel, & Macnnaughton, 2010). Clearly, if we simply developed ways of reducing waste, our need to develop new technologies would be reduced.

One area pivotally to improving global food security is soil health. Soil not only provides a medium for plant growth, it also provides valuable ecosystem services not limited to bioremediation, water filtration, and nutrient cycling (Brevik et al., 2015). Keesstra et al. (2016) reported while certain current “hot topic” environmental issues such as anthropogenic climate change, desertification, and protection of biodiversity all have large multilateral environmental agreements (MEAs) soils are often overlooked and underappreciated in their role in the aforementioned issues of bioremediation, water filtration, and nutrient cycling. Brevik et al. (2015) reported that most soil science literature is narrow and much focused, and that a more holistic and integrated approach is required to address larger environmental issues. While examining certain socio-economic factor it is important to keep in mind the hard biological constraints soil health has on food security.

In an oversimplified view, yield production (temporarily ignoring socioeconomic factors) can be seen as a function of biotic and abiotic factors. Quantitative models such as Schlenker and Lobell’s (2014) shows country level yields against weather data to determine a casual linkage. Schlenker and Lobell (2014) however, notes the fact that “diversity in access to factors such as land, credit, markets, and technology” often mask key differences. A recent report FAO (2014) stated that “sustained political commitment” is amongst the most important pre-requisites for achieve hunger eradication (a causal problem of food insecurity). The FAO (2014) promotes institutional reform as a catalyst to achieving global food security. Clearly, socioeconomic factor have a large if not often misunderstood impact on food security.

Socioeconomic factors are notorious different to analyse the magnitude and scope of their impact. This is confounded in quantitative models, of socioeconomic factors are primarily qualitative. Lobell and Burke (2010) report that there is heavy reliance upon numerical models that designed to emulate crop growth. Lobell and Burke (2010) later report that these numerical models are primarily draw upon and leverage scientific research. Yet, while inputting binary quantities for parameters such as precipitation and insolation, numerically estimating the effect of stronger legal institutions, prudent policy and proactive political decisions is very difficult. While new models do offer some flexibility, more quantitative socioeconomic factors such as HDI, GINI, and gross domestic product (GDP) per capita are required for quality, transparency and consistency in crop-climate modelling.
Despite a proliferation of crop data, which should theoretically increase the power of the crop modelling, long-term crop yield models remain notoriously inaccurate (Di Paola, Valentini, & Santini, 2016). Rötter, Carter, Olesen, and Porter (2011) reported that many of current climate-crop models are out date and fail to incorporate the recent advances in scientific literature. Rötter et al. (2011) went on to report that modellers often fail to quantify the uncertainty of the model leading forecasting poor in both scope and accuracy. Lobell and Burke (2010) suggested that “statistical models, as compared to CERES-Maize (which are based off of historical trends), represent a useful if imperfect tool for projecting future yield responses”. Despite the increase in data available to input, rapid advance in computing power and more precise parametrization, powerful statistical models still struggle to make complicated, long-term predictive models of chaotic systems such as the food system. Some more modern forecasting and predictive modelling scenarios allow for the wholesale input of introduce economic, environmental, demographic and legal variables. Despite this Thomas and Kielman (2009) reported food and agriculture needs analytics on a scale currently unavailable.

Another non-technical area that needs to be investigated is the role that socioeconomic policy may play in boosting production. For instance, many authors write that socioeconomic and institutional factors play a major (yet poorly understood) role in determining how much food a farmer produces and whether they can remain productive during an environmental shock such as a drought (Adger, 2006; Brooks, Adger, & Kelly, 2005; Patt, Klein, & Leinert, 2005; Smit & Skinner, 2002; Watts & Bohle, 1993). Case study based research on Ethiopia demonstrated this point by showing that during the 1980s, governance and economic problems meant that the population was unable to adapt to drought (Comenetz & Caviedes, 2002). As a result, the drought that in turn triggered the famine that claimed approximately one million lives was minor when measured in terms of its impact on rainfall and similar sized droughts caused nothing like the hardship a decade earlier or later (Fraser, 2007). Therefore, many social scientists argue that harvests and yields (which is the amount of harvest obtained per ha) are a function of biophysical factor such soil fertility, precipitation and soil moisture, as well as socioeconomic factors such as available labour, education, wealth, and governance (Fraser et al., 2011; IPCC, 2014; Watts & Bohle, 1993).

Most of the work done on the interaction between socioeconomic factors and harvests is like the Ethiopian study cited above in that it is qualitative and case based. Hence to date, socioeconomic insights have been difficult to integrate into global models of food supply and demand. While there are a few studies that quantitatively explore the socioeconomic factors that are important in determining food production, much more work needs before it will be possible to successfully bring together socioeconomic, demographic and environmental data to model future food supply and demand (Fraser, Simelton, Termansen, Gosling, & South, 2013; Simelton, Fraser, Challinor, Dougill, & Forster, 2012).

One area where an investigation of socioeconomic factors is particularly warranted is on what socioeconomic factors might enable farmers to increase yields. For instance, according to Mueller et al. (2012) many parts of the world, and particularly much of African and Asia, only produces <30% of what it potentially could produce. A quick evaluation of the data provided by Mueller et al. (2012), however, suggest that socioeconomic factors may influence these results. More particularly, while parts of South Africa and Tanzania (amongst other countries) produce close to 100% of what they theoretically could, other parts of Africa only produce 10% of their potential, suggesting that farm management, inputs, and other socioeconomic factors play a huge role in determining outputs. Hence, identifying social, political and economic strategies to increase the crop yield needs to be both a scientific and social policy priority of the highest importance. In this context, the objectives of this paper are to:
(1) Integrate spatial socioeconomic and crop harvest data to quantify how socioeconomic factors may have the potential to increase crop yields.

(2) Simulate the effect of different hypothetical socioeconomic policies on yields thus providing a preliminary assessment of policy priorities.

This paper, therefore, represents an important early step in the field of research devoted to better understanding the reasons for smaller yield and the potential that regions might have to increase yield if socioeconomic factors better favoured food production.

2. Data and methods

2.1. Data

The overarching purpose is to identify and evaluate socioeconomic variables significant in determining yield. In terms of dependent variables on yield, we used rice, wheat and maize yield data (http://www.geog.mcgill.ca/~nramankutty/Datasets/Datasets.html) for the year 2000 at the 0.25 degree grid cell level. These data are based on the publication by Monfreda, Ramankutty, and Foley (2008).

A closer look on the spatial distribution of crop yield globally shows that the highest yield of maize, wheat and rice was 22.7, 10.0 and 11.9 tons/ha, respectively, but there are areas where the yields were as low as just a few kg/ha. Unsurprisingly, there is a great difference in the yield performance in different climatic regions and crops, and higher crop yields are observed to be higher in cold climatic regions compared to tropical climatic regions. Average yield estimates show that the highest average of wheat yield was in temperate regions, while both maize and rice yields were higher in cold climatic regions. The average yield of rice was 2.58, 2.86, 5.17 and 5.54 tons/ha in the tropical, arid, temperate and cold regions, respectively. Similarly, the average yield of wheat was 1.73, 1.94, 3.26 and 2.62 tons/ha in the tropical, arid, temperate and cold regions, respectively. Likewise, maize yields were 1.90, 2.76, 4.34 and 4.66 tons/ha in the tropical, arid, temperate and cold regions, respectively (Table 1). Economic region-based yield data show that all crops in high income regions produce higher yields compared to other regions. Unsurprisingly, poor economic regions produced lower levels of crop yields. Average rice, maize and wheat yield in high income regions was 6.4, 6.7 and 3.8 tons/ha, respectively, whereas poor income regions produced only 2.2, 1.6 and 2.0 tons/ha of rice, maize and wheat, respectively.

Table 1. Average crop yields (tons/ha) by climatic zone and economic regions in 2000

| Climatic zone | Maize (tons/ha) | Rice (tons/ha) | Wheat (tons/ha) | Economic regions | Maize (tons/ha) | Rice (tons/ha) | Wheat (tons/ha) |
|---------------|----------------|---------------|----------------|-----------------|----------------|---------------|----------------|
| Tropics       | 1.904 (1.066)  | 2.576 (1.443) | 1.728 (1.198)  | Poor            | 1.584 (0.872)  | 2.173 (1.211)  | 1.994 (1.434)  |
| Arid          | 2.760 (3.493)  | 2.859 (1.764) | 1.938 (1.245)  | Lower middle    | 2.748 (2.569)  | 4.206 (2.228)  | 2.492 (1.555)  |
| Temperate     | 4.341 (2.845)  | 5.174 (2.304) | 3.261 (1.812)  | Upper middle    | 3.070 (1.798)  | 3.027 (1.891)  | 2.378 (1.720)  |
| Cold          | 4.455 (1.910)  | 5.544 (1.184) | 2.617 (1.165)  | High            | 6.744 (2.999)  | 6.416 (1.366)  | 3.805 (1.875)  |

Note: Figures in parenthesis are standard deviations.

*Nb the term “climatic region” refers to a world climatic classification by a famous scientist Köppen. Based on this classification world is divided into four regions: tropical, arid, temperate and cold (for the details please see The Köppen Climate Classification System).

*Nb the term “income region” refers to a classification of world countries into four economies as: low income, lower middle income, upper middle income and high income based on the gross nation income per capita (for the details please visit www.worldbank.org).
In terms of independent socioeconomic variables we used the following sources (FAO, 2011; Human Development Index, 2013; International Futures, 2009) to obtain the following variables:

1. GDP/capita (a proxy for how many resources a farmer in a country has);
2. Gini coefficient (a measure of income inequality and a proxy for how well distributed resources are);
3. The amount of GDP/capita derived from a country’s agricultural sector (a measure of the commercial importance of agriculture in a country); and
4. Fertilizer use intensity, measured in kg/ha cropland (which is both important in itself, as well as being a proxy for farmers’ access to modern agricultural resources).
5. Human Development Index (HDI) (a composite index made up of education, health and incomes)

2.2. Spatial regression models
Using these data, we used spatial regression models to explain yield in terms of the socioeconomic variables. To do this, we used already established methods to combine socioeconomic and gridded data (KC, 2005, 2011a, 2011b) that involved:

1. Preparing a continuous thematic raster layer for the country level socioeconomic variables;
2. Combining the raster layers with the grid cells in GIS environment (ARC GIS v10) that contained the distribution of each crop’s yield, thus providing us with grid cells that contained both the socioeconomic and crop yield data together. This meant that although crop yield data varied in each grid cell, all the grid cells within a specific country had the same value for the four socioeconomic variables. Although this is a limitation of the study, this is inevitable when using available data but should only obscure, rather than create trends.
3. The combined crop-yield and socioeconomic grid cells were exported to SPSS (v20) where multivariate regression were carried out by taking crop yield as the dependent variable and the socioeconomic factors as independent variables.
4. Estimated yield and impact maps for different scenarios were constructed by exporting the regression results back into the GIS platform (ARC GIS v10).

2.3. Policy scenarios
Next, we used the spatially explicit multiple regression models to simulate the effect of four hypothetical policy scenarios on cereal harvests. To do this, we first divided countries into four categories depending on whether they fell in low, lower middle, upper middle or high income categories (World Bank, 2009). Then, we calculated the effect of “improved socioeconomic policy” where we modeled the impact on yield if all countries increased their fertilizer use to 95% of that of the top fertilizer-using country within that income category (e.g. fertilizer use in all low-income countries was increased to 95% of fertilizer use by the top low-income country). We used the same approach to simulate the effect of income redistribution (where each country’s Gini coefficient was changed to 95% of the best Gini coefficient within the income category), economic growth (where the GDP/cap for each country was improved to 95% of the top GDP/cap of each income group) and an “HDI improvement” scenario, which was based on improving the HDI (where the HDI for each country was changed to 95% of the top HDI of each income group). Our decision to change the values of these socioeconomic variables to 95% of the best-performing country within an income class followed Foley et al. (2009) who calculated how much food could be produced globally if areas were to produce 95% of the most productive area in the same agro-ecological zone (Foley et al., 2009). There may be differences on marginal effect of increasing and/or improving socioeconomic impact from place to place. However, our scenario analysis has not taken this into account that is a limitation of the study as our scenario analysis was based on the linear regression model.
3. Results

3.1. Model results
As noted in the methods section, a GIS-based multivariate regression model for rice, maize and wheat was established where crop yield (tons/ha/yr) was the dependent variable and a range of socioeconomic variables were used as the explanatory variables. Using a stepwise approach, the following variables were found to be highly significant for all three crops ($p < 0.01$): HDI, fertilizer intensity, GINI coefficient and GDP per capita. These models also have a good explanatory power, and the $R^2$ for maize, rice and wheat models are 0.655, 0.458 and 0.352 respectively (Table 2). Our modelled yields are similar to the published ones. Overall, the model does a good job of simulating previously published yield data. Figure 1 shows the correspondence between the modelled yields (right hand panel) and published results (left hand panel) on global cereal yields. It is important to note that the model does not intend to predict the precise yield for a crop in any particular grid cell; instead the goal is to regionalize the current yield situation and use statistical dependencies as the basis for simulating the effects of possible different socioeconomic policy scenarios.

Overall, this model produce intuitively obvious results and the yield for all three grain’s increase with HDI, GDP/capita and fertilizer intensity, and more equitable income distribution. With regards to the spatial distribution reflected in the estimated maps (Figure 1, right hand panel), it was observed that low income countries reflected the combined effect of smaller HDI, low GDP and higher value of GINI coefficient, whereas upper middle and high income countries represented the combined impact of good income distribution and high GDP. This reflects the differences of socioeconomic conditions of the farmers and the policy framework in the different regions of the world.

| Table 2. Coefficient of multivariate regression model explaining the yield for maize, rice and wheat production |
|-------------------------------------------------------------|
| * $R^2 = 0.655.$  | ** $R^2 = 0.458.$ | *** $R^2 = 0.352.$ |
| **Maize** | **Beta** | **Standard error** | **t-value** | **p-value** |
| Constant | 2.168 | 0.034 | 63.837 | 0.000 |
| GDP capita | 0.146 | 0.001 | 224.514 | 0.000 |
| Fertilizer intensity | 0.010 | 0.000 | 156.404 | 0.000 |
| Gini coefficient | −4.301 | 0.054 | −79.719 | 0.000 |
| HDI | 1.358 | 0.053 | 25.764 | 0.000 |
| **Rice** | **Beta** | **Standard error** | **t-value** | **p-value** |
| Constant | 0.749 | 0.038 | 19.545 | 0.000 |
| GDP capita | 0.030 | 0.001 | 24.564 | 0.000 |
| Fertilizer intensity | 0.012 | 0.000 | 159.451 | 0.000 |
| Gini coefficient | −1.383 | 0.069 | −19.917 | 0.000 |
| HDI | 3.259 | 0.071 | 45.850 | 0.000 |
| **Wheat** | **Beta** | **Standard error** | **t-value** | **p-value** |
| Constant | 1.316 | 0.038 | 34.263 | 0.000 |
| GDP capita | 0.019 | 0.001 | 33.758 | 0.000 |
| Fertilizer intensity | 0.010 | 0.000 | 226.738 | 0.000 |
| Gini coefficient | −3.016 | 0.051 | −58.665 | 0.000 |
| HDI | 1.709 | 0.052 | 33.020 | 0.000 |
3.2. Impact of improving socioeconomic condition on global food production

As noted in the methods section, the final stage of this project was to simulate the effect of four different policy scenarios as a way of identifying the possible effect of different kinds of socioeconomic interventions on yield. First, we divided countries into four income categories (low, lower middle, upper middle or high) and then we simulated the effect of policies by using the models presented in the previous section to predict changes in rice, maize, and wheat yield if the socioeconomic conditions in all countries improved to 95% of the best performing country in that income category. For the “increased fertilizer” scenario, we simulated the effect on yield if all countries increased their fertilizer use to 95% of that of the top fertilizer-using country within that income category (e.g. fertilizer use in all low-income countries was increased to 95% of fertilizer use by the top low-income country). This resulted in four different scenarios that provide a rough order-of-magnitude assessment of how the following different types of policy may affect food production: (1) an improved human development scenario that was based on raising each country's HDI to 95% of the best performing country within an income category; (2) an equitable income scenario that was based on reducing the Gini coefficient of all countries to 95% of the best performing country; (3) an increased GDP scenario; and (4) an increased fertilizer scenario.

3.2.1. Improved human development scenario

Our first scenario was to simulate the effect of policy that aimed to improve a country's HDI, which is a composite index made up of average education, longevity and wealth. As such, we hypothesize that farmers in countries with a high HDI will have higher human capital and access to greater assets than farmers in low HDI countries and this should translate into better yields. Based on the regression models, we anticipate that an increase in HDI would result in significantly higher rice,
wheat and maize yields in all countries. In particular, Figure 2 shows large changes observed in poor countries where yields are expected to double from below 2 tons/ha to over 4 tons/ha. In addition, Figure 2 shows such yield increases are possible in many parts of Africa, while increases of up to 50% are possible in many of the developing countries of Asia and up to 30% in Latin America. This scenario suggests that increasing HDI could result in an additional 6.8 million tons of maize production globally. While this is only a 1.35% increase, increases are much more significant in the developing world and Table 3 shows that maize production could increase by more than 21% in poor countries. Likewise, 34 million more tons of rice are produced under this scenario. Similar to maize, the percentage increased is highest in poor economic regions. Wheat follows a similar trend; about 14 million tons of wheat can be expected through HDI improvement that is concentrated in poor countries (see details in Table 3).

3.2.2. More equitable income distribution
Our second scenario was to explore the effect of better income distribution within a country on harvest based on the hypothesis that farmers in countries with more equitable income distribution will be better able to invest in farms and farm practices on average. To do this, we used the GINI coefficient, which is a measure of income inequality (where a high GINI coefficient is a country where incomes are inequitably distributed) and a proxy for how well resources are distributed. When ran the yield models presented in the previous section by changing each country’s GINI coefficient to be 95% of the best performing country within each income category, we observe the models predicting that maize, rice and wheat yield will all increase in a manner consistent with the results presented above on the HDI scenario. In contrast with the HDI scenario, however, there is less spatial variation.
While the current maize, wheat and rice yield in much of the developing countries is below 2 tons/ha, results of the GINI scenario predicts the yield per hectare of rice, maize and wheat will reach and exceed 3–4 tons/ha (Figure 3). More specifically, Figure 3 demonstrates that yield increases of 100% are possible in many parts of Africa, Latin America and even some parts of Asia with respect to maize and wheat production. Additionally, Figure 3 shows the possibility of increasing rice yield by about 50% in many countries in Africa, Latin America and some Asian countries such as Thailand and China. Table 3 shows global production increasing under this scenario by 73 million tons of maize, 15 million tons of rice and 44 million tons of wheat production. Proportionally, these increases are most apparent in poor economic regions, however the gross contribution in tons is highest from middle and high income countries.

### Table 3. Effects of four different socioeconomic policy scenarios on maize, rice and wheat production in poor, lower middle, upper middle and high income countries

|                         | HDI improvement scenario | GINI improvement scenario | GDP improvement scenario | Fertilizer improvement scenario |
|-------------------------|--------------------------|---------------------------|--------------------------|--------------------------------|
| Δ in production (m. ton)| %                        | Δ in production (m. ton)  | %                        | Δ in production (m. ton)        |
| Maize                   |                          |                           |                          |                                |
| Poor                    | 2.72                     | 21.07                     | 4.55                     | 35.25                          | 1.84                         | 14.25                         | 106.10                         | 19.44                         | 22.23                         | 172.14                         |
| Lower middle            | 2.58                     | 1.74                      | 20.48                    | 13.80                          | 16.47                        | 11.10                         | 75.03                          | 50.56                         |                                |
| Upper middle            | 1.38                     | 1.78                      | 24.4                     | 31.35                          | 15.42                        | 19.82                         | 63.26                          | 81.28                         |                                |
| High                    | 0.10                     | 0.03                      | 23.89                    | 7.79                           | 72.37                        | 23.61                         | 127.02                         | 41.44                         |                                |
| Total                   | 6.79                     | 1.24                      | 73.32                    | 13.44                          | 106.10                       | 19.44                         | 287.54                         | 52.69                         |                                |
| Rice                    |                          |                           |                          |                                |                              |                              |                                |                                |                                |
| Poor                    | 11.40                    | 11.54                     | 2.31                     | 2.34                           | 0.625                        | 0.63                          | 45.78                          | 46.34                         |                                |
| Lower middle            | 22.38                    | 5.49                      | 10.76                    | 2.64                           | 8.48                         | 2.08                          | 261.81                         | 64.19                         |                                |
| Upper middle            | 0.38                     | 2.99                      | 1.13                     | 9.02                           | 0.41                         | 3.26                          | 8.00                           | 63.68                         |                                |
| High                    | 0.15                     | 0.53                      | 0.4                      | 1.46                           | 0.82                         | 2.98                          | 6.47                           | 23.60                         |                                |
| Total                   | 34.30                    | 6.27                      | 14.60                    | 2.67                           | 10.33                        | 1.89                          | 322.06                         | 58.91                         |                                |
| Wheat                   |                          |                           |                          |                                |                              |                              |                                |                                |                                |
| Poor                    | 1.27                     | 16.93                     | 0.42                     | 5.63                           | 0.09                         | 1.14                          | 7.47                           | 99.91                         |                                |
| Lower middle            | 9.41                     | 4.99                      | 17.33                    | 9.20                           | 3.51                         | 1.86                          | 142.10                         | 75.39                         |                                |
| Upper middle            | 2.87                     | 4.34                      | 8.77                     | 13.25                          | 3.11                         | 4.69                          | 84.31                          | 127.33                        |                                |
| High                    | 0.29                     | 0.15                      | 17.20                    | 9.02                           | 17.00                        | 8.92                          | 171.48                         | 89.95                         |                                |
| Total                   | 13.84                    | 3.06                      | 43.73                    | 9.66                           | 23.70                        | 5.23                          | 405.36                         | 89.52                         |                                |

Source: Data sources are: (1) harvest data (Monfreda et al., 2008); (2) socioeconomic data (FAO, 2011; Human Development Index, 2013; International Futures, 2009).

3.2.3. Increased GDP scenario
The third scenario is based on GDP/capita, and comes from the hypothesis that farmers in wealthy countries will have access to more resources and hence obtain higher yields. Broadly speaking results are consistent with the other scenarios presented here, and increasing GDP/capita increases yield, and that low income regions benefit the most from this. Unlike to previous two scenarios this scenario shows that the middle and high income countries will be benefitting more than the
developing countries in all three crop production (Figure 4). Figure four also shows the possibility of increasing a yield over 50% in many parts of the world with regards to maize production. The impact of GDP on rice and wheat production is lower than for maize production. Nevertheless, the model predicts a 15% increase in both rice and wheat yield under this scenario. The impact of increased GDP can be seen everywhere across the globe, yet in all three crop production, the biggest impact can be expected in many African countries (Figure 4). Overall, this scenario projects the following increases: 106 million tons of maize, 10 million tons of rice and 24 million tons of wheat, which translates into a 20% increase for maize, 5% for wheat and 2% for rice. Unlike HDI and GINI scenarios, however, this scenario shows that both absolute and proportional increases are highest in the developed world, particularly for maize production (Table 3).

3.2.4. Increased fertilizer scenario
Another determining factor of crop yield and harvest is the amount of fertilizer used to produce the crop. The intensity of fertilizer use, measured in kg/ha, therefore, is both important in itself as well as being a proxy for farmers’ access to modern agricultural resources. Simulated yield for maize, rice
and wheat under the increased fertilizer scenario is significantly higher than the base situation. Figure 5 shows the percentage of yield increased as a result of increased fertilizer and results presented in here are broadly similar to the other three scenarios. When comparing all four scenarios, the results show that the impact of increasing fertilizer is very strong with the developing countries benefiting the most from increased fertilizer usage. Here it shows the possibility of increasing a yield over 500% in many parts of Africa. Also, there will be a possibility of increasing crop yields up to 200% in East Asian and Latin American countries, and up to 100% in the remaining developing countries. In the high-income areas, the crop harvest situation will not be impacted very much. In terms of global food production, 288 million more tons of maize, 322 million more tons of rice and 405 million more tons of wheat may be produced under this scenario. Like other scenarios, the percentage increase of maize, rice and wheat is much higher in poor and middle income countries. However, in the case of volumetric contribution, there will be higher volumetric increment in poor and middle income countries in rice production. But in the case of maize and wheat, percentage increase will be higher in poor economic regions; however, the volumetric contribution will be much greater from high income countries (see details in Table 3).
4. Discussion and conclusion

Three results stand out. First, our paper demonstrates the importance of socioeconomic factors in determining yields; the variables explored in this analysis explained 65.5, 45.8 and 35.2% of global maize, rice, and wheat harvests, respectively. This analysis demonstrates the potential for increasing food production through socioeconomic policy along alongside other forms of agricultural adaptation strategies (Lobell et al., 2008). Based on this analysis, we estimate it is possible to increase rice, maize and wheat production by at least 72%, which is approximately what many experts suggest, will be necessary to avert future food crises (Godfray, Beddington et al., 2010).

Second, our models show the largest proportional change in yields were obtained in poorer countries, whereas the largest absolute changes occurred in richer countries. For instance, the fertilizer scenario shows that poor countries could increase their maize production by 172% or 22 million tons, while rich countries could increase their production by 41% or 127 million tons. Different scenarios on yields highlighted the disparate effects of policy on richer and poorer parts of the world as evidenced by the results in Figures 2–5, which suggest that in many parts of Africa, yields could be increased by over 500% with increased fertilizer application and by 50–100% with a more equitable income distribution. Our results, show the potential for socioeconomic policy to boost relative and absolute agricultural productivity in very poor parts of the world, echoing calls by (Juma, 2011; Kaplinsky, 2011) for a new technological approach to help African and Asian farmers reach their potential. The proportional effect of these policies highlights a policy dilemma. Since many academics argue that global food production must increase by 50–100% over the next fifty years, the results presented here suggest that policies such as subsidizing fertilizer rich countries will increase global

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Figure 5. Modelled percentage change in maize, rice and wheat yield for “Increased fertilizer”. In this scenario, we modeled the impact on yield if all countries increased application of fertilizer to 95% of the top fertilizer application data within that particular income category (so all low income countries’ fertilizer application were increased to 95% of the amount of fertilizer used by the top low income country).

Source: Data sources are: (1) harvest data (Monfreda et al., 2008); (2) socioeconomic data (FAO, 2011; Human Development Index, 2013; International Futures, 2009).
yields more than a similar policy in the developing world. This naturally leads to a broader discussion of whether “global” or local food systems are more effective at providing food security (Altieri & Rosset, 2002; Anderson, 2010). For instance, the US drought in the summer of 2012, like the Russian drought in the summer of 2010, caused commodity prices to skyrocket, causing widespread poverty and food insecurity, demonstrating the danger of global dependence on a handful of productive areas. Hence, many argue that food security is better achieved by investing in national or even local food systems (Torrez, 2010). In summary, academics suggest simplistic approaches to simply boost yields in the rich countries will have little effect on food security in the developing world where access to markets, poverty, agricultural technology, and income distribution are key (Tomlinson, 2011).

Third, our results highlight the complex ways that socioeconomic variables influence production. For instance, the effects of income distribution on yields for rice is highest in upper-middle income countries. These sorts of observations are similar to results presented by Patt et al. (2010) and Simelton et al. (2012) whose results suggest middle-income countries experience worse impacts from similarly-sized climatic events than richer or poorer countries. Simelton et al. (2012) hypothesize that this may be because an unintended consequence of economic growth is the dismantling of traditional agricultural practices which render food systems more vulnerable to climatic shocks. Simelton et al. (2012) also hypothesize that this vulnerability may diminish “modern” farming practices are adopted. The results presented in our paper are consistent with the aforementioned results, highlighting the complex interaction between socioeconomic and agricultural factors.

The overall contribution this paper demonstrates that if scholars and policymakers want to address the challenges of feeding the future, then socioeconomic factors must be taken seriously. Socioeconomic factors must be included as vital dimensions to be explored alongside the climatic, demographic and technological issues that currently dominate most scholars’ approach to food security. Until we better integrate socioeconomic with biological and demographic factors, it is unlikely we will ever obtain a fully robust understanding of when, where and how global food security may be threatened, and without such an understanding we will never be able to develop appropriate, effective and efficient policy.

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