Global agriculture and carbon trade-offs

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Feeding a growing and increasingly affluent world will require expanded agricultural production, which may require converting grasslands and forests into cropland. Such conversions can reduce carbon storage, habitat provision, and other ecosystem services, presenting difficult societal trade-offs. In this paper, we use spatially explicit data on agricultural productivity and carbon storage in a global analysis to find where agricultural extensification should occur to meet growing demand while minimizing carbon emissions from land use change. Selective extensification saves ~6 billion metric tons of carbon compared with a business-as-usual approach, with a value of approximately $1 trillion (2012 US dollars) using recent estimates of the social cost of carbon. This type of spatially explicit geospatial analysis can be expanded to include other ecosystem services and other industries to analyze how to minimize conflicts between economic development and environmental sustainability.

cropland expansion | food security

One of the primary challenges of the 21st century will be to meet growing demand for agricultural output while preserving essential ecosystem processes on which both long-term agricultural production and human well-being depend. Growing demand for food, feed, fuel, and fiber has led to conversion of natural grasslands and forests and reduced the flows of many important nonmarketed ecosystem services, such as carbon storage, water filtration, and habitat provision (1). Tropical forests are especially important for carbon storage and habitat for biodiversity, but 55% of new agricultural land in the tropics came from conversion of forests (2). Agriculture also uses 92% of the annual global water footprint (3). Despite this, nearly one billion people are food insecure, meaning they regularly fail to consume enough calories to lead an active healthy life (4). Due to rising population and incomes, the United Nations Food and Agriculture Organization (FAO) projects global food demand to grow by ~70% from 2000 to 2050 (5), whereas others have projected growth of 100–110% (6).

Agricultural production can be increased through intensification (higher yields with more fertilizer, pesticide and water inputs, multiple cropping, shorter fallow periods and improved seed varieties) and extensification (expanding to more hectares). Although intensification is expected to play a major role in meeting expanded demand, extensification is also likely to occur. FAO forecasts intensification will account for 80% of the future increase in global agricultural production with extensification accounting for 20% (70–30% split in developing countries) (5). It is possible in biophysical terms that all of the increase in demand could be met by intensification, especially through closing "yield gaps" between high productivity regions (e.g., North America) and low ones (e.g., Sub-Saharan Africa) (7–9). However, numerous social, political, and economic factors constrain intensification. Low-yield regions often suffer from political instability, lack of infrastructure, and the inability of poor farmers to invest in fertilizers, equipment, and other inputs. Moreover, the rate of increase in crop yields has been declining. Although the average annual increase in global yields between 1961–2007 was 2.92% for wheat, 1.91% for rice, and 2.47% for maize, the FAO predicts yield increases of only 0.86% for wheat, 0.63% for rice, and 0.83% for maize between 2005/2007 and 2050 (5). Climate change may also reduce future yields (10, 11). Even when it is possible to intensify, it may be more profitable for farmers to extensify instead.

We use a geospatial global analysis to identify where extensification should occur to minimize the negative impacts of extensification on the provision of ecosystem services. We illustrate the approach with an analysis of trade-offs between extensification and carbon storage because we have readily available global data on carbon. We find that selective extensification, taking into account both food production and carbon storage, preserves dramatically more carbon storage than a business-as-usual (BAU) extensification scenario that expands production proportionally in all areas. The general geospatial approach can be extended to include other activities beyond farming (e.g., urban development or forestry) and other ecosystem services beyond carbon storage with the main constraint being the availability of suitable global data.

Prior spatially explicit studies analyze trade-offs between agricultural production and multiple ecosystem services at local or regional scales (e.g., refs. 12–17), or national scales (18–20). Other studies analyze spatially explicit trade-offs globally (21–23). We extend the analysis of West et al. (23) using a selection approach capable of estimating the maximum possible amount of carbon stored consistent with meeting increased crop demand. We translate production of 175 different crops into production of consumable calories rather than using dry harvest weight to better reflect the real goal of increased food production. We also value the carbon storage using estimates of the social cost of carbon. Our work provides a spatially explicit counterpart to global agricultural analyses using national level data (24–27).

We use global high-resolution spatial data for 5×5-min grid cells ($\sim 10 \times 10$ km near the equator) on crop cultivation (28, 29) and carbon storage (30) to locate selective extensification. We derive a biophysical indicator of crop advantage (CA) by calculating the ratio of total calories produced to the loss of carbon stored for each grid cell with extensification: $CA = CY/\Delta C$, where CY represents caloric yield per grid cell aggregated over 175 crops using the current mix of crops grown (28), and ΔC is the tons of carbon storage lost (including aboveground, belowground, and soil carbon) per grid cell when a cell is converted from grassland or forest into cropland. To calculate carbon

Significance

We assess how to meet growing demand for agricultural production to minimize impact on the environment. Higher levels of population and affluence may require expanding land in agriculture by converting grasslands and forests to cropland. Such conversions often reduce valuable ecosystem services. Our research identifies where are the best places to expand agricultural production that minimize the loss of one ecosystem service, carbon storage. We show that selectively choosing where to expand agriculture saves over $1 trillion (2012 US dollars) worth of carbon storage relative to a proportional expansion.

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storage loss per unit area, we compare carbon storage in potential natural vegetation to carbon storage in cropland. Carbon storage in potential natural vegetation and the methods for calculating cropland carbon are from West et al. (23) (see *Methods* and *SI Appendix* for details).

We use the *CA* score for grid cells to minimize the loss of carbon storage while meeting increased food demand. The geospatial global selection routine ranks all grid cells by *CA* and extensifies crop production in the cell with the highest *CA* score, subject to constraints on feasibility of extensification in the cell. We continue to extensify in the highest ranked remaining cell until future food needs are met (see *Methods* and *SI Appendix* for details).

We limit the amount of extensification that can occur within a grid cell to reflect realistic constraints. We do not allow expansion to occur in grid cells in which less than 5% or over 95% of the area is cultivated. Grid cells above 95% are assumed to be fully used. Grid cells below 5% typically include areas not suited to crop production such as deserts without irrigation, high-altitude areas, latitudes too far north or south to grow crops, and protected natural areas. Areas such as the Amazon or Congo Basin have grid cells with less than 5% in current cultivation due to lack of infrastructure, access to markets, or other factors, but that could be productive. However, these areas are extremely rich in carbon and therefore have low *CA*. We ran sensitivity analyses that allowed expansion into these grid cells, but they were not chosen for crop production in the selection routine.

In grid cells with current cultivation between 5% and 95% cultivation, we constrain extensification to reflect heterogeneity within the grid cell. Even in grid cells with high crop yields, there will be portions of the grid cell that have steep slopes, poor soil, protected or developed lands that are unsuitable for crop expansion. We provide an example of how this type of spatial heterogeneity could limit extensification on an example grid cell in *SI Appendix*. We lack detailed global data to make cell-by-cell extensification constraints. Instead, we adopted the following generic rules to constrain extensification. For grid cells with current cultivation between 15% and 95% cultivated, extensification can close up to 75% of the gap between current cultivation and 95% cultivation. For grid cells with current cultivation between 5% and 15%, we allow extensification up to a multiple of four times current cultivation. We do a sensitivity analyses with different extensification constraints to show that our results are robust to different constraints (*SI Appendix*).

We keep the mix of crops in each grid cell constant. We choose not to change crop mix for two reasons. First, the caloric content of crops does not reflect the reason some crops are grown or their full value (e.g., crops grown for fiber or other nonfood uses, that have cultural significance in a region, or that contain important micronutrients). Selecting for caloric content risks losing production of other valuable characteristics. Second, our analysis is focused on the general trade-off between agricultural production and carbon storage. Although optimizing on crop mix would reduce the amount of extensification needed to meet increased demand, inclusion of crop mix changes do not change the general nature of the trade-off between agricultural production and carbon.

The results of this selection procedure are compared with a BAU simulation. We define BAU as increasing the share cultivated in each grid cell by the percent necessary to meet increased demand. So, for example, with a 50% increase in area a grid cell with 10% crop coverage would expand to 15%, whereas a cell with 20% coverage would expand to 30%. BAU increases are subject to the same feasibility constraints and limits as described above. The difference between the BAU simulation and the selective solution is that BAU assumes a uniform proportional expansion while the selective solution expands according to CA. We also conducted analysis with different BAU scenarios to test robustness (results are included in *SI Appendix*).

We focus our analysis on a future scenario in which we must produce 100% more calories than in 2000 [in line with estimates from Tilman et al. (6)] with 25% coming from extensification and 75% coming from intensification gains. We also vary both changes in overall demand for crops and the proportion of increased production coming from extensification versus intensification to

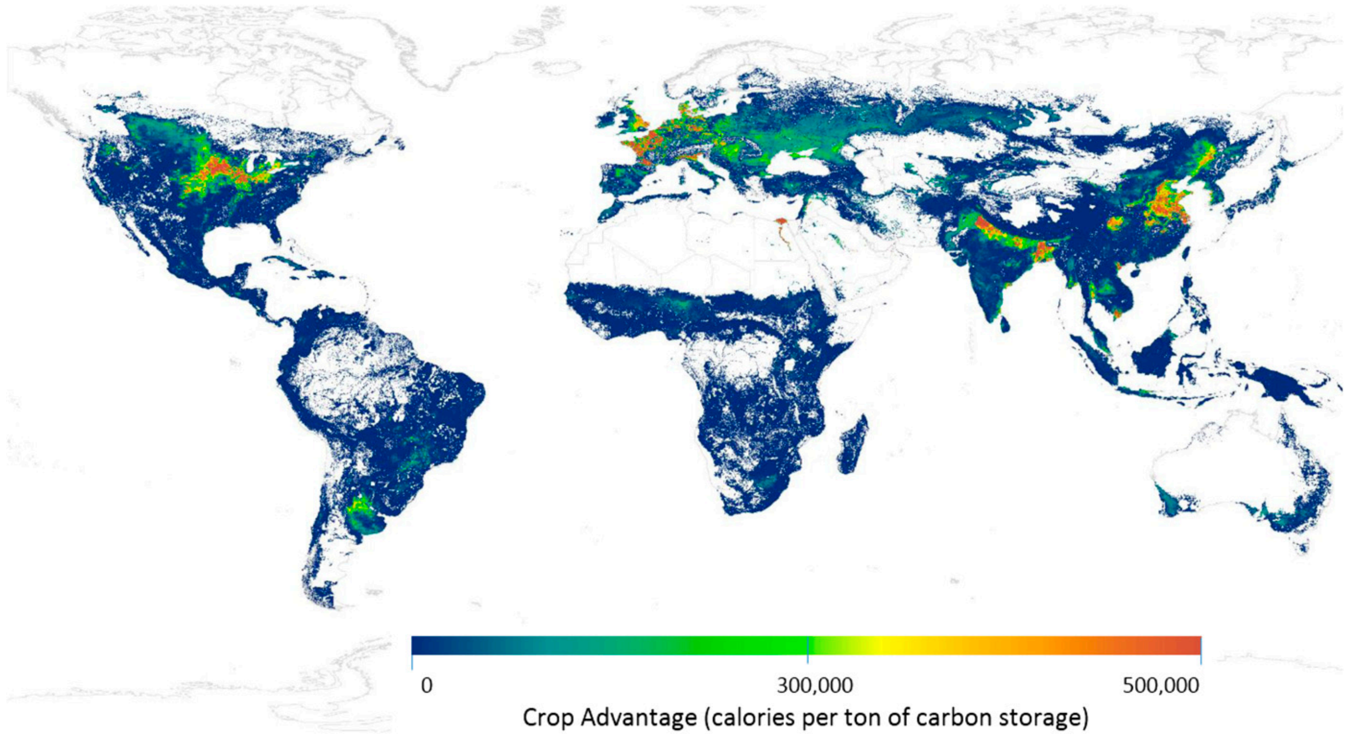

Fig. 1. Crop advantage (CA). Ratio of aggregate calories produced divided by carbon storage on each 5 × 5-min grid cell. Red values indicate areas where crop cultivation is comparatively advantaged over carbon storage.

show sensitivity of results to the level of increased production needed (*SI Appendix*).

Results

We identify areas with the largest crop advantage (Fig. 1). Grid cells with the highest *CA* score produce 300,000 calories per ton of carbon storage lost with crop expansion. Areas that are currently heavily farmed, including the Corn Belt of the US Midwest, parts of Western Europe, the Nile Valley, the Ganges River Plain, and eastern China, have very high *CA* values. Much of the tropics have relatively low *CA* both because of low crop yields and high carbon storage values. Areas with no color have no observed cultivation.

We then identify which grid cells are best selected for extensification to meet expanding demand for crops while conserving as much carbon storage as possible. We compare the selective solution with the BAU solution to highlight areas in which it is better to concentrate agricultural expansion (Fig. 2). Many areas with the highest *CA* values are already heavily cultivated and have little available land for further extensification. In the selective solution, extensification increases at the edges of currently intensively farmed areas. The selective solution has greater extensification on the edges of the US Corn Belt, parts of Western Europe, and eastern China. The center of the US Corn Belt, the Nile River Valley, and much of the Ganges River Plain are little changed because little land is still available for extensification.

Parts of Eastern Europe, the Ukraine, Russia, and several pockets in Southeast Asia are extensified more heavily in the selective solution than in BAU. Much less extensification occurs in the Philippines, Indonesia, Southern India, parts of Sub-Saharan Africa, and Central America where *CA* is low.

An advantage of our geospatial approach is that it can assess land use changes at many levels of aggregation from the global scale down to individual 5 × 5-min grid cells. To illustrate more detailed regional patterns, we show *CA* and selective extensification for two specific regions: the US Corn Belt and Southeast Asia (Fig. 3). At higher resolutions, we see in more detail that selective extensification occurs along the edges of currently intensively cropped areas in the US Corn Belt and several rich river valleys in Southeast Asia, such as the Mekong Delta and Red River in Vietnam, the Irriwaddy River Basin in Myanmar, and the Chao Phraya River Basin in Thailand. Conversely, fewer new hectares are cultivated and more carbon is stored in most other areas in the selective solution compared with BAU. These are areas where soils are less productive or the topography is less suited to cropping.

By concentrating extensification in areas with high crop advantage, much more carbon storage occurs under the selective solution compared with BAU extensification (Fig. 4). Large amounts of carbon storage are preserved in Indonesia and other parts of Southeast Asia, India, Sub-Saharan Africa, and Central America. Areas with greater extensification under the selective solution show reduced carbon storage, but the losses are far less than the gains elsewhere (see *SI Appendix* for detailed comparison). On a global level, selective extensification results in preserving 5.89 billion metric tons of carbon compared with BAU. This figure rises if more demand must be met through extensification. For example, with 50% of demand met through extensification, selective extensification results in 12.08 billion metric tons of carbon saved (*SI Appendix*).

Increasing carbon storage in terrestrial systems can reduce the amount of atmospheric CO_2 and potentially reduce damages from climate change. Using results of a survey of 232 published estimates of the social cost of carbon for different discount rates (31), we find that the value of the additional carbon stored in the selective solution versus the BAU scenario ranges from $0.44 trillion to $1.30 trillion in 2012 US dollars depending on the assumed pure rate of time preference, with a value of just over $1 trillion with a 1% pure rate of time preference (Table 1).

Discussion

Given the large projected increases in demand for agricultural crops, it is likely that at least some of this increase will have to be

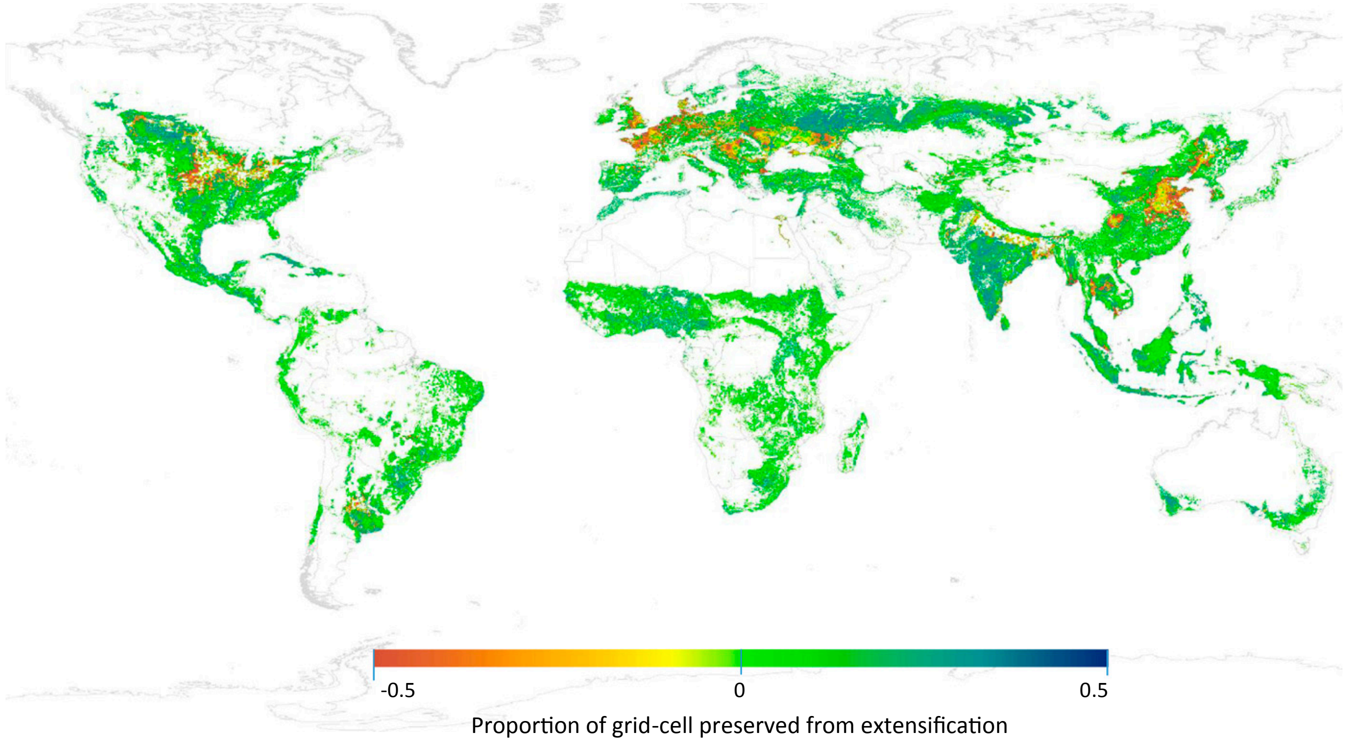

Fig. 2. Comparison of selective extensification versus BAU. Both the selective and the BAU simulation produce 100% more calories and assume 25% of the calories come from extensification. The blue and green shading indicate areas where less extensification would occur under the selective solution compared with BAU. The red and yellow shading indicates areas where more extensification would occur under the selective solution compared with BAU.

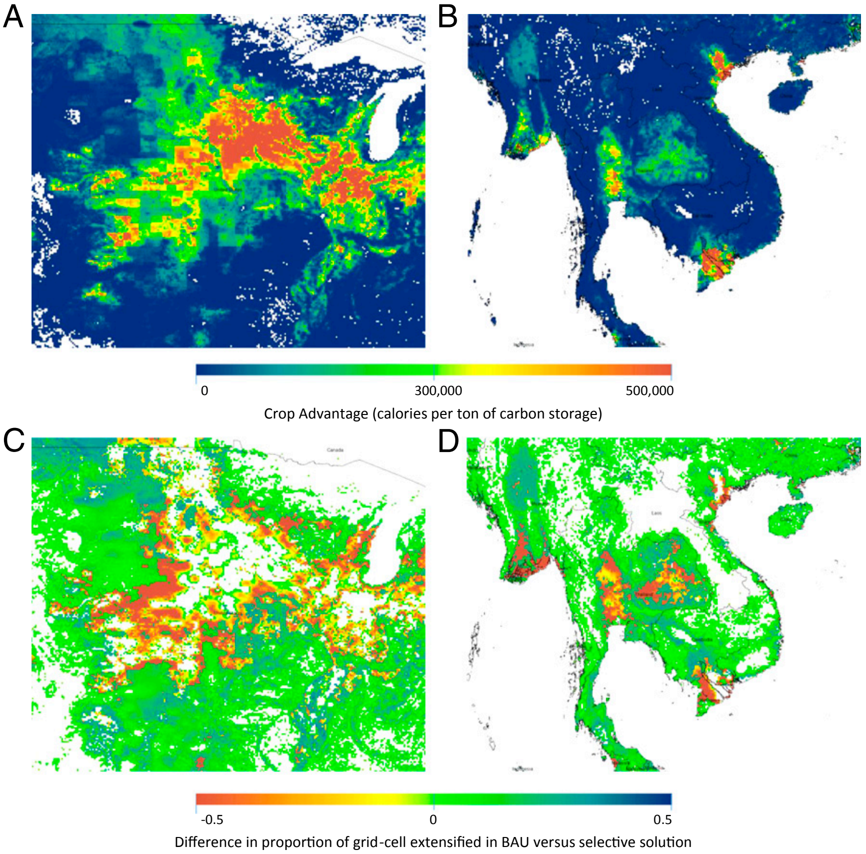

Fig. 3. Crop advantage and extensification in selective and BAU simulations for the US Corn Belt (*Left*) and Southeast Asia (*Right*). (*A* and *B*) Crop advantage. (*C* and *D*) Difference in extensification in BAU simulation versus selective solution.

met by expanding the amount of land devoted to agricultural production. Agricultural extensification comes at the expense of natural habitats (forests and grasslands) that provide carbon storage and many other ecosystem services. In this paper, we show that by finding the best locations to extensify and the best locations to conserve natural habitats, we can meet increased crop demand while maintaining far higher levels of carbon storage than following a BAU proportional expansion. To minimize the loss of stored carbon with extensification, the expansion of cultivated hectares should be concentrated on the extensive margin of areas that are currently heavily cultivated, as these areas tend to have the highest crop advantage (i.e., the greatest increase in crop production per unit loss of stored carbon). Following the selective strategy would conserve an estimated 5.89 billion metric tons of carbon in natural environments by 2050, with an estimated social value of $1.06 trillion at $181 per ton C, compared with a BAU scenario.

In this paper, we considered only agricultural extensification and one form of natural capital, carbon storage, but the optimization principles we used are general and can be extended to include multiple types of natural capital and ecosystem services, as well as considerations of agricultural intensification. Modeling the trade-offs from intensification requires estimating the increase in yield with intensification and the impact on natural capital and ecosystem services. For example, how does increased application of nitrogen fertilizer affect yields, water quality, and greenhouse gas emissions? Modeling approaches for inclusion of multiple ecosystem services has advanced rapidly over the past few years (e.g., ref. 32). Analysis of the impact of land use choices to maximize a bundle of ecosystem services has been done at regional (e.g., ref. 17) and national scales (e.g., ref. 19). To date, lack of consistent global datasets has hindered application of high-resolution analysis at global scales. However, work on global datasets also is advancing rapidly (e.g., ref. 33). Our approach could be expanded to incorporate other datasets on ecosystem services and integrated with models such as InVEST (34) that calculate estimates of the provision of a number of ecosystem services as a function of land use and land management choices. In general, it should be possible to solve for the combination of optimal choices of extensification and intensification to find how best to increase agricultural production while maintaining the highest valued bundle of ecosystem services. Doing so would require information on grid cell costs of intensification as well as the implicit values that society places on the relative importance of various ecosystem services. If a broader array of ecosystem services and a broader set of actions (intensification and extensification) are analyzed, it is likely that the total social value from selective solution compared with BAU would be many times greater than found here.

This analysis makes a number of assumptions about the rate of growth in future demand for crops and the proportion that can be met by intensification and extensification, as well as how much extensification can occur in various grid cells due to subgrid cell heterogeneity. We analyzed the effect of changes in these assumptions in *SI Appendix*, where we show that changing assumptions affects the specific magnitudes but not general tenor of the trade-offs between agricultural expansion and carbon storage.

Our analysis of selective extensification does not include several other potentially important factors such as climate change, or changes in broader economic factors such as changes in quality of inputs, trade barriers, infrastructure, and transport systems. Future climate change will likely influence yields and the provision of other ecosystem services and change the results. Similarly, changes in quality of inputs, trade barriers, infrastructure, and transport systems can influence the yields and desirability

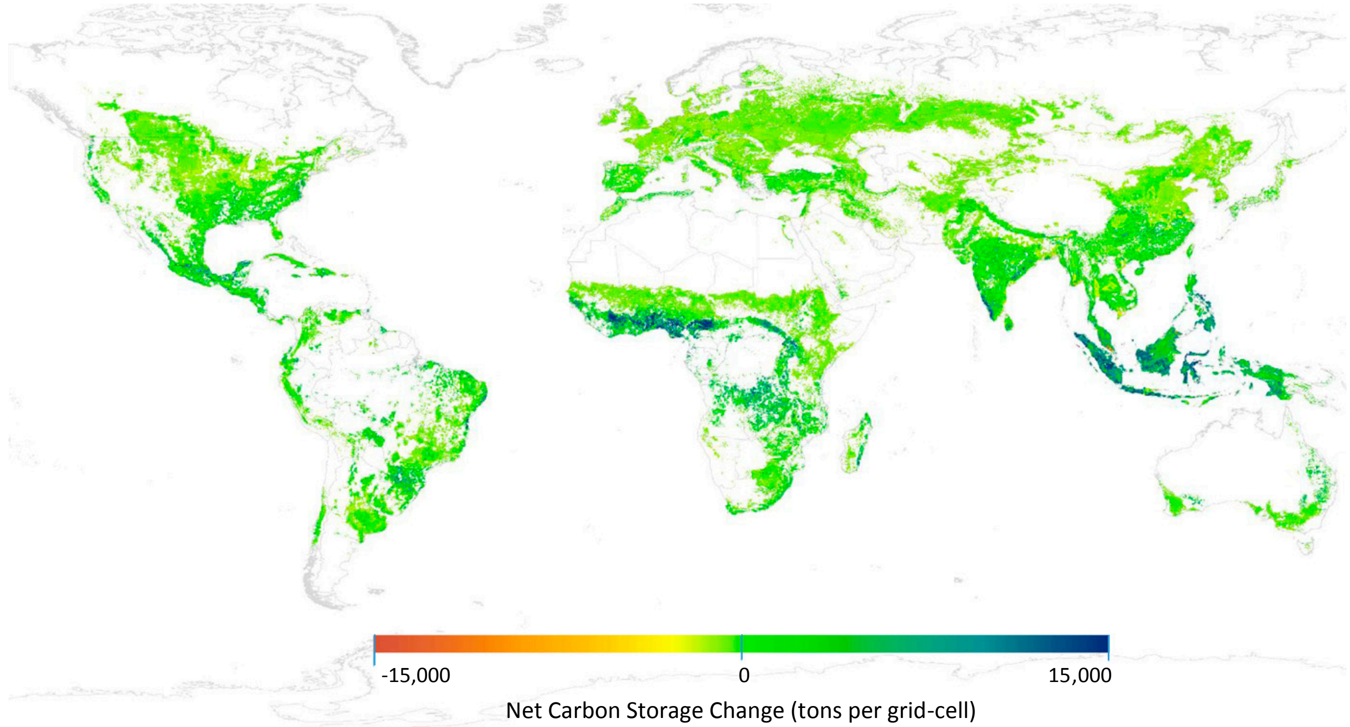

Fig. 4. Net carbon storage change. Tons carbon storage preserved per grid cell under selective solution versus under BAU. Blue and green indicate areas where larger amounts of carbon storage occur under the selective solution versus BAU, whereas yellow indicates that less carbon is stored under the selective solution (areas of greater extensification).

of agricultural production in different locations, thereby changing the relative crop advantage by location. For example, high transport costs would generate added value to producing output closer to consumers. Each of these changes will affect the quantitative results but not the overall conclusion about the importance of selective extensification.

Nonetheless, showing what is possible and actually achieving it are not the same thing. Like West et al. (23), Foley et al. (7), and others, this paper shows what is feasible in biophysical terms. We show how careful consideration of both carbon storage and crop yield can maximize carbon storage while meeting agricultural production goals, subject to assumptions about sub-grid cell heterogeneity that may limit extensification options. Moving closer to desirable outcomes requires attention to institutional, political, social, and economic factors, because billions of people must change what they are doing. These changes will require recognition by political leaders and the general public of the value of carbon storage (and other ecosystem services). Otherwise, there will be little push for carbon policies such as establishing a price for carbon storage, and therefore little incentive for landowners to incorporate carbon or value of other ecosystem services into their decision making. Without this, we are likely to see a trajectory much closer to BAU than the selective extensification path.

Table 1. Value of carbon storage saved while producing 100% more calories

	Pure rate of time preference		
Value measure	0%	1%	3%
Social cost of carbon, 2012 dollars	$221	$181	$75
Value saved in base scenario, trillions 2012 dollars	$1.30	$1.06	$0.44

Values for the social cost of carbon are the mean value for the fitted distribution in Tol (31), adjusted to 2012 US dollars.

As an example of national policy redirection, Brazil has incorporated the value of preventing deforestation in the Amazon and elsewhere into its national Forest Code. The rate of deforestation in Brazil has been reduced by 83% since 2004 (35). This reduction was achieved primarily by the creation of new protected zones and stricter enforcement of land use regulations. Our analysis can help build on such successes by more precisely identifying areas that are good candidates for protected status and areas where agricultural production should be encouraged.

Methods

The crop advantage measure for each grid cell is defined as the marginal benefit of extensifying land in different locations and is defined for each 5 × 5-min grid cell with geospatial coordinates (x, y) as follows:

$$CA_{xy} = \frac{CY_{xy}}{\Delta C_{xy}}, \qquad [1]$$

where CY_{xy} is the per-hectare calorie yield in each grid cell and ΔC_{xy} is the per-hectare carbon storage loss that would occur if the grid cell was converted from forest or grassland to cultivation. CY_{xy} was calculated by combining data from the EarthStat dataset (28, 29) with FAOSTAT (4) values on caloric content of each food group. We calculated the per-hectare calorie yield of each xyth grid cell, CY_{xy}, as follows:

$$CY_{xy} = \sum_{i=1}^{175} Y_{ixy} * A_{ixy} * C_i, \qquad [2]$$

where Y_{ixy} is the dry weight in tons per hectare of the ith crop, A_{ixy} is the fraction of crop area planted to crop i, and C_i is the caloric content of the ith crop per ton. C_i is calculated as follows:

$$C_i = \left(\frac{S_i * 365}{Q_i}\right), \qquad [3]$$

where S_i is the variable from FAOSTAT's Food Balance Sheet dataset named "Food supply (kcal/capita/day)" and Q_i is FAOSTAT's "Food supply quantity (kg/capita/yr)." This process created a gridded map of worldwide per-hectare calorie yield. We calculated per-grid cell calorie yield by multiplying the per-hectare calorie yield by the amount of hectares present in each grid cell, which we used for calculating aggregate calorie production. When summed globally, per-grid cell calorie yield matches the FAO's estimate of total caloric production.

To calculate the change in carbon storage (ΔC_{xy}) with extensification, we use the method from West et al. (23). We subtract the amount of carbon storage (aboveground and belowground) in potential natural vegetation $(PNVC_{xy})$ and one-quarter of the soil carbon associated with potential natural vegetation (SC_{xy}) from crop carbon (CC_{xy}) that would exist on the grid cell if it was fully extensified:

$$\Delta C_{xy} = CC_{xy} - PNVC_{xy} - 0.25(SC_{xy}). \qquad [4]$$

Data on potential natural vegetation carbon comes from West et al. (23), which used carbon values from the tier 1 methodology of the Intergovernmental Panel on Climate Change (30), applied to potential natural vegetation data (36). To estimate soil carbon loss, we used gridded data on global soil organic carbon density (measured as kilograms of carbon per square meter to a depth of 1 m) from International Geosphere-Biosphere Programme (37) interpolated to match the resolution of the data from Monfreda et al. (28) and Ramankutty et al. (29).

To calculate the carbon stored in each of the 175 crops, we assumed crop carbon storage of annual herbaceous crops is equal to their annual net primary productivity (23), calculated as follows:

$$CC_{xyi} = \frac{DF_i * C\ * Y_{ixy}}{R_i}, \qquad [5]$$

where CC_{xyi} is the crop carbon of the ith crop on the xyth grid cell, Y_{ixy} is the dry weight in tons per hectare of the ith crop on that cell, DF_i is the proportion of dry matter of the yield for crop i, C is the carbon content of dry matter (0.45 g C per g dry matter), and R_i represents the proportion of the crop that leaves the farm (rather than remaining on the field or belowground). Carbon stocks in woody crops were calculated in Gibbs et al. (38). Summation over each of the 175 crops gives C_{xy}, the total carbon that that would be stored in the grid cell's crop cover if the grid cell was fully converted to cultivation (assuming the same proportional crop mix as in 2000). Finally, we converted ΔC_{xy} to be the change in carbon per hectare extensified.

Assuming that annual net primary production is equal to a crop's biomass likely overstates the amount of stored carbon in crops because the biomass is only storing carbon for part of the year. In the context of identifying which areas are better left natural, this assumption makes our conclusions and estimation of saved carbon conservative. Accounting for crop carbon, however, has a very small impact on the overall results because the amount of carbon able to be stored in crops is much less than the amount of natural carbon storage in most locations.

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