Trading carbon for food: Global comparison of carbon stocks vs. crop yields on agricultural land

Paul C. Westb,d,1, Holly K. Gibbst, Chad Monfreda, John Wagnerf, Carol C. Barforda, Stephen R. Carpenterb, and Jonathan A. Foleyf

Abstract

Expanding croplands to meet the needs of a growing population, changing diets, and biofuel production comes at the cost of reduced carbon stocks in natural vegetation and soils. Here, we present a spatially explicit global analysis of tradeoffs between carbon stocks and current crop yields. The difference among regions is striking. For example, for each unit of land cleared, the tropics lose nearly two times as much carbon (~120 tons ha−1 vs. ~63 tons ha−1) and produce less than one-half the annual crop yield compared with temperate regions (1.71 tons ha−1 yr−1 vs. 3.84 tons ha−1 yr−1). Therefore, newly cleared land in the tropics releases nearly 3 tons of carbon for every 1 ton of annual crop yield compared with a similar area cleared in the temperate zone. By factoring crop yield into the analysis, we specify the tradeoff between carbon stocks and crops for all areas where crops are currently grown and thereby, substantially enhance the spatial resolution relative to previous regional estimates. Particularly in the tropics, emphasis should be placed on increasing yields on existing croplands rather than clearing new lands. Our high-resolution approach can be used to determine the net effect of local land use decisions.

Results

What Is the Distribution of Average Crop Yields? Annual average crop yields vary by an order of magnitude across the globe depending on crop type, soil type, climate, and management. At present, average crop yields in temperate regions are typically double those in the tropics (Table 1). However, yields vary within each climate region (Fig. 1).

What Is the Change in Carbon from Converting Natural Ecosystems to Croplands? The average carbon loss resulting from converting natural ecosystems to croplands is highest in the tropics, largely because tropical forests store much more biomass carbon than any other biome (10). Our analysis estimates that nearly two times as much carbon is lost for each converted hectare in the tropics than in temperate regions (Table 1 and Fig. 2). Carbon stocks are predicted to increase in a small fraction of the area in our analysis (<0.09%). Areas with increases were most common in sparsely vegetated grasslands and deserts, which may now be irrigated. Variation within each of the climate regions is driven by different distributions of ecosystem types, climate, and soils.


The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

1To whom correspondence should be addressed. E-mail: pcwest@wisc.edu.

This article contains supporting information online at www.pnas.org/cgi/doi/10.1073/pnas.1011078107.

1To whom correspondence should be addressed. E-mail: pcwest@wisc.edu.

www.pnas.org/cgi/doi/10.1073/pnas.1011078107

PNAS | November 16, 2010 | vol. 107 | no. 46 | 19645–19648
Tropical vegetation currently stores recovered by the greenhouse gas savings from biofuel use (15). The carbon lost by clearing new land for biofuel production can be (Fig. S1 and Table S1). It can take decades, even centuries, before cleared lands that are currently managed as grasslands or pastures release mature or degraded forests (14). These cleared tropical forests release ~95–215 more tons of carbon than previously cleared lands that are currently managed as grasslands or pastures (Fig. S1 and Table S1). The high carbon loss per unit crop yield in the tropics results from the combined highest average carbon loss from conversion coupled with the lowest average yield values (Table 1 and Figs. 1 and 2). Although management practices play an important role in crop yield, the spatial variability of the tradeoff is driven more by changes in carbon stocks than by distribution of crop yields.

**What Is the Tradeoff Between Carbon Stocks and Crop Yields?** Using the two analyses described above, we quantified and mapped the tradeoff between carbon stocks and crop production by calculating the ratio of carbon loss to crop yield in each ~10-×10-km cell. Our results show strong differences in the carbon–crop tradeoff among regions. Nearly three times as much carbon has been lost per ton of crop yield in the tropics compared with temperate regions (Table 1 and Figs. 3 and 4). The high carbon loss per unit crop yield in the tropics results from the combined highest average carbon loss from conversion coupled with the lowest average yield values (Table 1 and Figs. 1 and 2). Although management practices play an important role in crop yield, the spatial variability of the tradeoff is driven more by changes in carbon stocks than by distribution of crop yields.

**Discussion**

Tradeoffs between crop yield and carbon storage have implications for meeting the global demand for food, fiber, and fuel as well as the need to mitigate climate change through carbon storage. Crop production is projected to increase by 50% to meet these needs by 2050, perhaps requiring ~100–200 million ha of new cropland, depending on genetic innovations, irrigation, fertilization, and tillage practices (11–13). This increase in demand is the result of increased population, a shift to meat-based diets, and biofuel production.

Cropland expansion during the 1980s and 1990s was greatest in the tropics (1). Over 80% of new tropical croplands in the 1990s replaced mature or degraded forests (14). These cleared tropical forests release ~95–215 more tons of carbon than previously cleared lands that are currently managed as grasslands or pastures (Fig. S1 and Table S1). It can take decades, even centuries, before the carbon lost by clearing new land for biofuel production can be recovered by the greenhouse gas savings from biofuel use (15–18). Tropical vegetation currently stores ~340 billion tons of carbon (19), which is 40 times more than annual global fossil fuel emissions (20). This vast tropical carbon reservoir is at risk; today, only 10.5% of the tropics is cropland, and future cropland expansion is projected to be greatest there (13, 21–13).

There is growing consensus that economic incentives are needed to maintain and increase forest cover to protect critical carbon reservoirs. In particular, international policies to reduce emissions from deforestation and degradation (REDD) using incentives to maintain forests using the carbon market have gained momentum. These emerging efforts could help balance the tradeoffs between carbon storage and crop production. Our results corroborate recommendations to concentrate reforestation and avoid deforestation in the tropics to have the greatest worldwide impact (24, 25). For example, even if tropical crop yields are doubled to yields comparable with those in temperate regions, clearing lands in the tropics still releases ~35 tons of carbon per ton of annual crop yield.

Despite the clear benefits of concentrating reforestation and forest conservation efforts in the tropics, several local and regional factors influence implementation. Although local land use change has global consequences for atmospheric greenhouse gas concentrations, choices are made locally and are influenced by local and regional food security, transportation costs, labor, poverty, and technology rather than global atmospheric carbon. Thus, local and global outcomes must be coupled to manage ecosystem services and assess their tradeoffs (26). This mismatch is particularly important in the tropics where agricultural lands are expanding at the highest rate and the carbon loss per hectare is highest. However, production increases will be difficult to achieve by intensification alone, because mechanized farming is not widespread in many of these developing regions. Natural ecosystems are likely to be maintained when crop production needs are met elsewhere and on lands where (i) crop yields are

**Table 1. Summary of crop yield, carbon stocks, and tradeoffs**

<table>
<thead>
<tr>
<th>Region</th>
<th>Percentage of region in cropland</th>
<th>Average annual dry yield, all crops (tons crops ha⁻¹ y⁻¹)</th>
<th>Average change in carbon stock from land conversion (tons C ha⁻¹)</th>
<th>Average tradeoff index (tons C ha⁻¹/tons crop yield ha⁻¹ y⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropics</td>
<td>10.5</td>
<td>1.7</td>
<td>−120.3</td>
<td>−76.9</td>
</tr>
<tr>
<td>Subtropics</td>
<td>13.5</td>
<td>3.3</td>
<td>−68.3</td>
<td>−27.0</td>
</tr>
<tr>
<td>Temperate</td>
<td>20.4</td>
<td>3.8</td>
<td>−62.9</td>
<td>−26.9</td>
</tr>
<tr>
<td>Boreal</td>
<td>1.4</td>
<td>3.7</td>
<td>−71.5</td>
<td>−37.0</td>
</tr>
<tr>
<td>Polar</td>
<td>&lt;1.0</td>
<td>2.2</td>
<td>−10.5</td>
<td>−4.7</td>
</tr>
</tbody>
</table>

![Fig. 1. Cropland distribution and average annual yield.](#) Croplands cover ~15 million km² (8). The weighted average dry crop yields per unit area for 175 herbaceous and woody crop types were calculated from data presented in Monfreda et al. (9). The highest yield regions are in temperate western Europe and North America, but high yields are also present locally within tropical regions.
marginal, (ii) the value of carbon outweighs the value of crops, and/or (iii) natural ecosystems provide multiple high-valued services such as water purification, recreation, or biodiversity conservation.

Although the patterns of the tradeoff between carbon stocks and crop yield provide useful insights for policy, the accuracy of the tradeoff ratio is often limited by data availability. Using the Intergovernmental Panel on Climate Change (IPCC) Tier 1 approach (27) to estimate carbon stocks in potential natural vegetation masks the variability caused by natural disturbance, topography, microclimate, and soil type. Therefore, estimates may be too high or too low for some locations (19). A recent study suggests that the default values used in this approach underestimate carbon stocks for ecosystems such as temperate moist forests (28). We also lacked carbon stock data for the majority of woody crops; however, this assumption likely has little effect on the overall analysis, because woody crops occupy only 9% of the total cropland. Although the World Soil Information (ISRIC) soil data represent the best comprehensive datasets of soil carbon estimates, we must note that knowledge of these stocks is somewhat uncertain (7, 29, 30). Furthermore, land management practices are not included in our analysis; thus, it does not account for the greenhouse gases emitted to generate the crop yield, such as the fertilizer production needed to produce the high yields in temperate regions. Other studies that accounted for additional aspects of the life cycle indicate that yield increases through increased fertilization and mechanization emit fewer greenhouse gases than older technology (31) and that the gains in greenhouse gas reduction outweigh the greenhouse gas costs of production (32). Pastures were excluded in this analysis, because we lacked production units equivalent to crop yield.

Tradeoffs of carbon stocks and crop yield provide a starting point for policy discussions and future research. Although our study omits life cycle emissions from crop production, it suggests that increasing yield on existing tropical croplands is preferable to clearing new land. To reduce future carbon emissions and meet crop demands, private and multilateral investments should focus on maintaining or restoring tropical forests and increasing yields through low petroleum inputs on existing cropland.

Land conversion and farming practices affect not only carbon storage but also other ecosystem services (33). Agriculture strongly affects soil and groundwater recharge, runoff, and nutrient regulation as well as ecosystems, species, and genome diversity of landscapes (2, 11, 12, 23, 34–36). Much more work is needed to understand how farming practices and potential technological improvements affect tradeoffs among crop yield, carbon storage, and other ecosystem services such as water availability, pest control, and pollination. Our work is a step to resolving the tradeoffs in...
the full portfolio of ecosystem services affected by land use and agriculture decisions.

Full accounting for the net effects of agricultural decisions must consider the global implications, such as displacement of land use activities to other regions, and their effects on multiple ecosystem services. Ecosystem services affected by agriculture include provisioning of food, fiber, and freshwater, regulation of climate through carbon storage as well as biophysical influence on regional air temperature and moisture, and cultural values of landscapes (2, 11, 23, 34, 36, 37). In addition, agriculture directly affects aspects of natural capital like heterogeneity of landscapes, which includes diversity of ecosystem types and species (12, 22, 23).

**Methods**

Average crop yield for each 10–100 km cell was weighted by each crop’s harvested area (9). Multicropping systems are accounted for in the harvested area data (9). Carbon stocks in potential natural vegetation were estimated by applying the IPCC Tier 1 methodology (27) to potential vegetation and soil datasets using a committed carbon flux approach (38). We then estimated carbon stocks of herbaceous crops using yield data and methods for calculating net primary productivity (NPP) (9) and assumed that annual NPP was equivalent to the standing carbon stock for most crops. This assumption is conservative, because aboveground biomass is only present for part of the year and then, harvested. Woody crop carbon stocks were estimated using IPCC Tier 1 methodology (27) and the extrapolation approach defined in Gibbs et al. (15). We estimated the change in terrestrial carbon storage from crop-land conversion by calculating the difference between carbon stocks in current croplands and potential vegetation. Using these analyses, we quantified and mapped the tradeoff between carbon stocks and crop production by calculating the ratio of carbon loss to crop yield (Fig. 3 and Table 1). Detailed methods for estimating carbon in natural vegetation and croplands are provided in SI Text, Fig. S1, and Table S1.

**ACKNOWLEDGMENTS.** Aaron Ruesch helped calculate soil carbon loss estimates. Mary Sternitzky helped create the figures. We thank George Allee for his editing suggestions and Gretchen Daily, Richard Houghton, and two anonymous reviewers for their helpful comments. We appreciate the invitation from Ruth DeFries to be included in this special feature. Funding for this research was provided by a Dr. Laurel Salton Clark Memorial Graduate Fellowship from National Aeronautics and Space Administration (NASA) and the Wisconsin Space Grant Consortium, NASA’s Interdisciplinary Science Program, a US Department of Energy Global Change Environmental Program Fellowship, and The Nature Conservancy.


18. Piñeiro G, Jobbágy EG, Baker J, Murray BC, Jackson RB (2009) Forests, agroforestry, and cultural values of landscapes (2, 11, 23, 34, 36, 37). In addition, agriculture directly affects aspects of natural capital like heterogeneity of landscapes, which includes diversity of ecosystem types and species (12, 22, 23).

Supporting Information

West et al. 10.1073/pnas.1011078107

S1 Text

Carbon Stock in Potential Natural Vegetation. We applied above- and belowground living biomass carbon stock values in the Intergovernmental Panel on Climate Change (IPCC) Tier 1 methodology (1) to a 5-min (~10 x 10 km) latitude–longitude gridded dataset of potential natural vegetation (2) using the method of Ruesch and Gibbs (3). The potential natural vegetation dataset was stratified by climate zones defined by the global ecological zones from the Food and Agriculture Organization (FAO) and continental zones, resulting in estimates that, in most cases, were specific to each coarsened climate–continent combination. Our approach complements previous efforts to estimate carbon stocks in current vegetation (3–5). Because the potential vegetation classification system contained a few types not contained in the IPCC Tier 1 methodology (1), we made assumptions for the following ecosystems:

- Savanna. We assumed the carbon stock of savanna to be 50% of the value of the dominant deciduous forest type within the ecological zone.
- Shrublands. We applied the shrubland values in the IPCC Tier 1 methodology (1) to areas defined as dense shrublands by Raman-kutty and Foley (2). We assumed that open shrublands had 25% of the carbon stock of dense shrublands in the same ecoregion.
- Temperate evergreen forest. We assigned the same carbon stock value for the dominant deciduous forest type also located within the ecoregion.
- Tundra. We assigned to tundra the same carbon stock values as boreal grasslands in the IPCC Tier 1 methodology (1).

Table S1 summarizes data used to create the global carbon stocks in the potential vegetation map. The map product is provided in Fig. S1.

Estimating Carbon Stock in Croplands. The above- and belowground living biomass carbon stocks of annual herbaceous crops are assumed to equal their net primary productivity (NPP). Herbaceous crop NPP was estimated from dry yield values (6) using a procedure widely adopted in the literature (7–11). The following equations were used to calculate the NPP of each herbaceous crop within each grid cell followed by an area-weighted average of the NPP of all crops to determine the average NPP for all such crops (Eqs. S1 and S2):

\[
NPP_i = EY_i \times DF_i \times C \div (HI_i \times R_i) \quad \text{and} \quad \text{[S1]}
\]

\[
NPP = \sum_{i=1}^{175} (NPP_i \div Area_i). \quad \text{[S2]}
\]

where \(i\) refers to an individual crop. In the numerator of the equation, \(EY\) is metric tons of economically valued yield per hectare, \(DF\) is proportion of dry matter of the economic yield, \(C\) is a carbon content of 0.45 g C g dry matter\(^{-1}\). In the denominator, \(HI\) indicates the harvest index, which is a measure of the proportion of total aboveground biological yield that is the economic yield of the plant, and \(R\) refers to the proportion of the belowground biomass relative to the total biomass of the plant.

Few carbon stock estimates exist for woody crops. For oil palm and coconut croplands, we extrapolated the IPCC Tier 1 methodology values (68 tons ha\(^{-1}\) and 88 tons ha\(^{-1}\), respectively) using the approach outlined in Gibbs et al. (5). For the remaining tree crops, we assumed 30 ton ha\(^{-1}\) of carbon. For woody shrub crops, such as blueberries, we assumed carbon stocks of 10 tons ha\(^{-1}\).

Estimating Soil Carbon Loss. We calculated the soil carbon in the top 1 m of soil using data from the World Soil Information (ISRIC) dataset (12). We assumed that conversion of natural ecosystems to herbaceous croplands reduced soil carbon by 25%. This 25% loss assumption is consistent with meta-analyses of changes to soil carbon after conversion to herbaceous croplands (13–15). We assumed that the soil carbon values in the ISRIC dataset represented a 25% reduction from their values before clearing the vegetation for herbaceous croplands.

Fig. S1. Carbon stocks in potential vegetation. The IPCC Tier 1 approach for estimating carbon stocks was applied to a potential natural vegetation dataset (2). Values ranged from 0 to 372 tons ha⁻¹.

Table S1. Carbon stock values for potential natural vegetation

Potential vegetation biome categories were cross-walked to match the IPCC Tier 1 categories (ecological and continental zones) used by Ruesch and Gibbs (3). All values are for above- and belowground living biomass. Soil carbon stocks are not included.