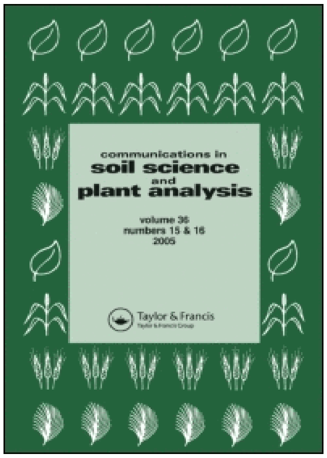

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Estimated land area increase of agricultural ecosystems to sequester excess atmospheric carbon dioxide

D. G. Wright [a]; R. W. Mullen [a]; W. E. Thomason [a]; W. R. Raun [a]
[a] Department of Plant and Soil Sciences, Oklahoma State University, Stillwater, OK, U.S.A.

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ESTIMATED LAND AREA INCREASE OF AGRICULTURAL ECOSYSTEMS TO SEQUESTER EXCESS ATMOSPHERIC CARBON DIOXIDE

D. G. Wright, R. W. Mullen,* W. E. Thomason, and W. R. Raun

Department of Plant and Soil Sciences, 044 Agricultural Hall, Oklahoma State University, Stillwater, OK 74078

ABSTRACT

An estimated 3.3 Pg carbon (C) is accumulating in the atmosphere annually, with carbon dioxide (CO_2) concentrations increasing approximately 1.5–2.0 ppm per year. The conversion of land to agroforestry, rangeland, and cropping systems has been identified as a possible option to offset rising CO_2 levels. The objective of this work was to estimate the increase in land area for the leading global cereal crops (maize, rice, wheat), temperate rangeland, and temperate forest ecosystems to sequester the surplus atmospheric C. Based on calculations and previously published data, maize cropping systems are the most efficient at sequestering C. An additional $6.7–7.6 \times 10^8$ha of maize would be required to assimilate the 3.3 Pg C yr^{-1}, a 477–543% increase in global

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*Corresponding author. E-mail address: rwm@okstate.edu

corn production. Agroforestry appears to be the only agricultural system that could realistically be implemented to reduce global CO_2 levels with a calculated increase of $4.6–4.6 \times 10^8$ha (a 52–66% growth in worldwide area). Also, the estimated net productivity of 6.7–7.1 Mg C ha^{-1} for temperate forests is significantly greater than the productivity of maize, rice, or wheat cropping systems, which ranged from 2.7–4.3 Mg C ha^{-1}. Increasing land area for agricultural production may not be the answer to the global C dilemma, but intensive management systems that result in increased soil organic matter are a significant part of the solution.

INTRODUCTION

Carbon dioxide (CO_2) is a greenhouse gas that is believed to contribute to global warming (1, 2). The concentration of CO_2 in the atmosphere is increasing by 1.5–2.0 ppm per year, giving rise to an approximate 0.5°C increase in global temperature (3, 4). Keeling and Whorf (5), report an increase in atmospheric CO_2 concentration from 280 ppm to a present level of 365 ppm over the past 60 years. Approximately 3.3 Pg C is added to the atmosphere each year from numerous natural and anthropogenic processes (6). The increase in atmospheric levels is primarily due to fossil fuel burning and deforestation (7). Additionally, the oxidizing of soil organic matter from cultivation has accounted for an estimated 6–25% of the 80 mg kg^{-1} increase in atmospheric CO_2 over the past 150 years (8).

To offset atmospheric accumulation of CO_2 and global warming, the conversion of land to agroforestry, rangeland, and no-till/minimum till cropping systems has been identified. Plant photosynthesis can increase the net carbon flux from the atmosphere to terrestrial ecosystems (9). Carbon sequestration of crops, grassland, and forest systems differs greatly and is difficult to predict due to poor understanding of the biogeochemical dynamics of C among plants, soil, and the atmosphere (10). Many scientists believe that agriculture can have the greatest impact in reducing atmospheric C due to our ability to intensively manage agriculture over long periods of time. The U.S. Department of Energy published a report that categorized the C sequestration potential of intensively managed biomes (11). Forestry displayed the highest level of potential C sequestration quantitatively with an estimate of 1–3 Pg C yr^{-1}, but qualitatively the sustained management of forests was ranked moderate. Likewise, the sequestration by cropping systems was assessed to be 0.85–0.90 Pg C yr^{-1} and ranked high in intensive sustained management. Rangeland sequestered 1.2 Pg C yr^{-1} and had a moderate ranking in sustained management. Increasing land area in agricultural production that sequesters greater concentrations of CO_2 appears to be an

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Table 1. Components Used for Calculating Global Land Area Increase in Maize, Rice, and Wheat Production Needed to Sequester Excess Atmospheric CO_2 Using Harvest Index and %C in Biomass

	Maize		Rice		Wheat	
Component	Value	Reference and/or Calculation	Value	Reference and/or Calculation	Value	Reference and/or Calculation
Average global yield in 1999	4.32 Mg ha^{-1}	FAO, 2000	3.84 Mg ha^{-1}	FAO, 2000	2.73 Mg ha^{-1}	FAO, 2000
Harvest index	50%	Sinclair, 1998; Dale and Drennan, 1997	50%	Sinclair, 1998	50%	Slafer et al., 1999
Total biomass per hectare	8.64 Mg ha^{-1}	4.32 Mg maize ha^{-1}* 0.5 (harvest index)	7.68 Mg ha^{-1}	3.84 Mg maize ha^{-1}* 0.5 (harvest index)	5.46 Mg ha^{-1}	2.73 Mg maize ha^{-1}* 0.5 (harvest index)
Percent C in biomass	50%	Fischer and Turner, 1978	50%	Fischer and Turner, 1978	50%	Fischer and Turner, 1978
Total C in biomass per hectare	4.32 Mg ha^{-1}	8.64 Mg maize ha^{-1}* 0.5 (%C)	3.84 Mg ha^{-1}	7.68 Mg maize ha^{-1}* 0.5 (%C)	2.73 Mg ha^{-1}	5.46 Mg maize ha^{-1}* 0.5 (%C)
Total atmospheric C excess	—	—	3.3×10^9 Mg	Follett and McConkey, 2000	—	—
Area required to sequester excess C	7.6×10^8 ha	3.3×10^9 Mg C/4.32 Mg C ha^{-1}	8.59×10^8 ha	3.3×10^9 Mg C/3.84 Mg C ha^{-1}	1.2×10^9 ha	3.3×10^9 Mg C/2.73 Mg C ha^{-1}
1999 global land area in production	1.4×10^8 ha	FAO, 2000	1.53×10^8 ha	FAO, 2000	2.14×10^8 ha	FAO, 2000
Estimated percent increase in global production to sequester excess CO_2	543%	$(7.6 \times 10^8$ ha$/1.4 \times 10^8$ ha$)*$ 100	561%	$(8.59 \times 10^8$ ha$/1.53 \times 10^8$ ha$)*$ 100	561%	$(1.2 \times 10^9$ ha$/2.14 \times 10^8$ ha$)*$ 100

environmentally friendly means for decreasing atmospheric C. Increased soil organic matter, higher biomass production, decreased nutrient loss, and improved soil and water quality are other benefits from increased sequestration in soil/plant systems (11). However, some ill effects of major land use change are degradation of sensitive ecosystems (from erosion of highly erodable land or desertification in arid regions), increased energy costs for production, and large economic investments. Schlesinger (12) noted that as agricultural production increases, the net C sequestered by the crop is nullified by the CO_2 released from fertilization, irrigation, and manuring. For example, the Haber-Bosch process produces 1180 kg CO_2 per 1000 kg N synthesized.

At this stage in earth's history, it is believed that mankind can make strides to decrease the current excess C accumulation in the atmosphere. Creating agricultural ecosystems that scrub CO_2 is a widely held solution to this global dilemma. The objective of this work was to estimate the amount of area required to annually sequester the 3.3 Pg C excess by three different cropping systems (maize, rice, or wheat), temperate forest, or temperate rangeland ecosystems.

RESULTS

Many scientists believe that agriculture is the answer to reducing the rising CO_2 levels in the atmosphere. The increase in global agricultural land area required to sequester the excess 3.3 Pg C per year is evaluated in this work. Terrestrial C storage and fluxes within plants are very difficult to quantify on a global scale, ranging from 420 to 830 Pg C in living plant tissue (13). Currently, a great deal of uncertainty exists concerning methods and models used to determine the total plant C pool. For this work, prior data from numerous sources is compiled to determine the total C sequestered per year for maize, rice, wheat, rangeland, and temperate forest ecosystems. The assumption that C sequestering ability is constant across varieties of corn, wheat, and rice is made for the calculations.

Maize Cropping System

Worldwide, maize ranks first in cereal grain production with an approximate 5.97×10^8 Mg produced in 1999 (14). This approach uses the mean harvest index and percent C in plant biomass along with average global maize yield (Table 1). To determine the total mass of C sequestered by the global corn crop, a worldwide mean yield of 4.32 Mg maize ha^{-1} (14) is divided by the 0.5 harvest index (15,16) for a total of 8.64 Mg biomass ha^{-1}. The total biomass per hectare is multiplied by the 50% C in maize tissue (17) resulting in a total of

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Table 2. Components Used for Calculating the Global Land Area Increase of Temperate Forest and Rangeland Ecosystems to Sequester Excess Atmospheric CO_2 Using Net Primary Productivity of Ecosystems from Amthor et al. (1998) Data

Component	Value	Reference and/or Calculation
Temperate forest ecosystem		
Mean net primary productivity of temperate forests per hectare	6.7 Mg C ha^{-1} yr^{-1}	Amthor et al., 1998
Total annual excess atmospheric C	3.3×10^9 Mg	Follett and McConkey, 2000
Area required to sequester excess CO_2	4.93×10^8 ha	3.3×10^9Mg C yr^{-1}/6.7 Mg C ha^{-1} yr^{-1}
Global land area currently under temperate forest	7.5×10^8 ha	Amthor et al., 1998
Estimated increase in global temperate forest area to sequester excess CO_2	66%	$(4.93 \times 10^8$ ha$/7.5 \times 10^8$ ha$) \times 100$
Temperate rangeland ecosystem		
Mean net primary productivity of temperate rangeland per hectare	3.5 Mg C ha^{-1} yr^{-1}	Amthor et al., 1998
Total annual excess atmospheric C	3.3×10^9 Mg	Follett and McConkey, 2000
Area required to sequester excess CO_2	9.43×10^8 ha	3.3×10^9Mg C yr^{-1}/3.5 Mg C ha^{-1} yr^{-1}
Global land area currently under temperate rangeland	1.25×10^9 ha	Amthor et al., 1998
Estimated increase in global temperate rangeland to sequester excess CO_2	75%	$(9.43 \times 10^8$ ha$/1.25 \times 10^9$ ha$) \times 100$

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4.32 Mg C ha^{-1} sequestered annually. Finally, the 3.3 Pg C (6) in the atmosphere is divided by the 4.32 Mg C ha^{-1} (14) to obtain a value of 7.4×10^8ha of maize per year required to assimilate the surplus C. To find the increase in global maize production, the 7.4×10^8ha is divided by the area under corn production in 1999, 1.4×10^8ha (14), and a 529% increase in total corn production is found. Using data published by Lohry (10), the estimated increase in maize production needed would be 476% beyond current production area.

Rice Cropping System

Rice production ranks second among cereals in hectares cultivated globally (14). For the increased area estimation of rice systems, the mean harvest index and percent C data is used for the first calculation. For this calculation, a mean global rice yield of 3.84 Mg ha^{-1} (14) is divided by a harvest index of 0.5 (15) to acquire a total biomass of 7.68 Mg rice ha^{-1} (Table 1). Then, the rice biomass per hectare is multiplied by the percent C, 50% (17), for a mean total C of 3.84 Mg C sequestered for every hectare of rice grown. Thus an area of 8.3×10^8ha is needed (3.3 Pg C/3.84 Mg C ha^{-1} rice) to remove the 3.3×10^9 Mg C. The area is a 544% increase from the 1.5×10^8ha under production in 1999 (14).

Wheat Cropping System

Wheat is the third ranking cereal crop with an approximate 5.9×10^8 Mg of grain produced in 1999 (14). The mean global wheat yield from the FAO (14) database records an average of 2.73 Mg wheat per hectare. The average yield is divided by the mean harvest index of 0.5 (18) and the quotient is multiplied by the 50% C (17) in the tissue to find a total of 2.73 Mg C ha^{-1} in the wheat biomass (Table 1). The final step is to divide the biomass C per hectare by the 3.3 Pg C in the atmosphere. This results in 1.2×10^9ha of wheat necessary to sequester the annual atmospheric C excess, which would be a 548% increase in global wheat production (2.14×10^8ha cultivated in 1999). The increase in wheat production necessary to sequester excess atmospheric C would be 467% beyond current production land area using Lohry (10) data.

Temperate Forest Ecosystem

The temperate forest ecosystem is chosen to represent the global region where agroforestry currently or potentially can be practiced. Dixon et al. (19) estimated that between 5.9–12.2 $\times 10^8$ha of land are technically suitable for the establishment of agroforestry in Africa, Asia, North and South America. For this work, the estimate by Amthor et al. (20) of 7.5×10^8ha of temperate and plantation forest is used for the first calculation. A second method is used to crosscheck these results and the estimate of 9.0×10^8ha of temperate forest by Bolin (21) will be utilized. Net primary productivity of temperate forests established through prior data is utilized for both calculations to determine the C sequestering ability of these ecosystems.

Using the data provided by Amthor et al. (20), a mean net primary productivity of 6.7 Mg C ha^{-1} yr^{-1} is assimilated in forest vegetation (Table 2). To find the area needed to sequester the excess atmospheric C, the 3.3 Pg C surplus is divided by 6.7 Mg C ha^{-1} yr^{-1} resulting in a total area of 4.9×10^8ha needed to sequester the excess 3.3 Pg C. Bolin (21) estimated a primary productivity of 7.1 Mg C ha^{-1} yr^{-1} for a temperate forest ecosystem. Dividing the 3.3 Pg C excess by the primary productivity generates a land area of 4.6×10^8ha needed to sequester excess atmospheric C. The areas calculated by Amthor (20) and Bolin (21) represent a global increase in temperate forestry of 66% and 52%, respectively.

Temperate Rangeland Ecosystem

Rangeland ecosystems cover a large geographic region, which includes shrubland, grassland, and open forest areas. Approximately 47% of the earth's land surface is occupied by rangeland (22). Due to the broad interpretation of a rangeland ecosystem, the estimation of the global land area and net primary productivity of range has differed greatly in prior research. Data from Amthor et al. (20) and Bolin (21) is used for the rangeland ecosystem calculations.

Amthor et al. (20) reported a mean net primary productivity for a temperate rangeland ecosystem of 3.5 Mg C ha^{-1} yr^{-1}. The 3.3×10^9 Mg excess of atmospheric C is divided by the 3.5 Mg C ha^{-1} yr^{-1} and a solution of 9.4×10^8ha is found (Table 2). This area constitutes an increase of 75% from the 1.25×10^9ha currently in rangeland. Bolin (21) documented a biomass production of 4.6 Mg C ha^{-1} yr^{-1} for a range system. Dividing the excess C by the productivity yields an area of 7.1×10^8ha. From the 9.0×10^8ha currently under range reported by Bolin, the 7.1×10^8ha increase is approximately a 79% rise in global land area.

DISCUSSION

The objective of this work was to compute the sequestering potential of agricultural ecosystems and the feasibility of converting land into temperate forest, rangeland, maize, rice, or wheat to reduce the atmospheric CO_2

concentrations. Tropical and temperate forests, temperate woodland, tropical savanna, and temperate grasslands are environments with suitable climates that most likely could support crop production. Of the total C sequestered by these ecosystems maize, rice, and corn cropping systems (the top three cereal crops grown worldwide) only account for approximately 4% of the C sequestered. Additionally, the net productivity of corn, rice, and wheat are considerably lower than native ecosystems. Other ecosystems exist that could be accounted for in the table, but the chosen ecosystems represent the largest biomes that man can conceivably replace with agriculture.

Although the calculations are simple and the estimates ignore numerous other factors, the areas computed provide a relative idea of the impracticality of agricultural land conversion to reduce atmospheric C. In particular, the millions of additional hectares needed for maize, rice, and wheat production would require vast amounts of resources, labor, finances, and suitable land. Agroforestry appears to be the most sensible agricultural system evaluated that mankind could realistically implement to reduce global CO_2 levels. With a net primary productivity of 6.7–7.1 Mg C ha^{-1}, temperate forestry ecosystems require less management and inputs than cropping systems and exhibit significantly higher productivity values over the cereal crops. A 52–66% increase of temperate forests is still improbable, but much more rational than the other ecosystems analyzed. Rangeland can also play a significant role by storing large volumes of soil organic C. Approximately 75% of terrestrial C is stored in the soil (11), therefore, agricultural systems that do not employ cultivation could substantially aid in C sequestration.

Transforming land into agricultural ecosystems cannot be viewed as a plausible solution to combat global warming. The environmental impacts associated with expanding global agriculture would be increased fossil fuel consumption, a rise in methane emission from rice paddies and NO_x from grassland ecosystems, and a decrease in soil organic matter. The conversion of native ecosystems into millions of agricultural hectares would significantly alter plant and wildlife habitats across the globe. Shifting land use could also change global nutrient cycling. For example, increased crop production will in turn cause greater plant ammonia loss that could impact atmospheric, oceanic, and freshwater nitrogen pools.

CONCLUSIONS

The conversion of land into agricultural ecosystems could improve the sequestration of atmospheric C; however, the effectiveness of this practice would be marginal due to the enormous land area conversion required to assimilate the 3.3 Pg of atmospheric C accumulating annually. Of the ecosystems evaluated in this work, temperate forests sequester more C per year (6.7–7.1 Mg C ha^{-1} yr^{-1}) and require the smallest net global increase in land area (an addition of $4.6–4.9 \times 10^8$ha) when compared to other systems. The maize cropping system is the most effective in C sequestration of the cereal crops calculated with an estimated potential of 4.3 Mg C ha^{-1} yr^{-1}, or 6.0×10^8 Mg C per year. Using this C sequestering potential for maize, an additional $6.7–7.6 \times 10^8$ ha of corn production would be needed to absorb the surplus atmospheric C. The worldwide land area under maize production in 1999 was 1.4×10^8 ha; therefore, a 476–546% increase in global maize production would be required. To realize the area calculated, land unsuitable for agriculture would likely have to be utilized. Furthermore, large volumes of natural and economic resources would be consumed in order to implement agricultural production in the areas needed to reduce the atmospheric CO_2 level. It is important to note that these calculations are for current emissions. If emissions increased or decreased, the static calculations reported here would obviously change.

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