CLIMATOLOGY

The potential of agricultural land management to contribute to lower global surface temperatures

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Removal of atmospheric carbon dioxide (CO_2) combined with emission reduction is necessary to keep climate warming below the internationally agreed upon 2°C target. Soil organic carbon sequestration through agricultural management has been proposed as a means to lower atmospheric CO_2 concentration, but the magnitude needed to meaningfully lower temperature is unknown. We show that sequestration of 0.68 Pg C year^{-1} for 85 years could lower global temperature by 0.1°C in 2100 when combined with a low emission trajectory [Representative Concentration Pathway (RCP) 2.6]. This value is potentially achievable using existing agricultural management approaches, without decreasing land area for food production. Existing agricultural mitigation approaches could lower global temperature by up to 0.26°C under RCP 2.6 or as much as 25% of remaining warming to 2°C. This declines to 0.14°C under RCP 8.5. Results were sensitive to assumptions regarding the duration of carbon sequestration rates, which is poorly constrained by data. Results provide a framework for the potential role of agricultural soil organic carbon sequestration in climate change mitigation.

INTRODUCTION

The uptake of atmospheric carbon (C) by plants and subsequent storage in soils may be an effective means to lower atmospheric carbon dioxide (CO_2) concentrations and to help mitigate climate change. Integrated assessment models (IAMs), which are used to explore future energy, land-use, and greenhouse gas (GHG) emission scenarios, currently rely on bioenergy with carbon capture and storage (BECCS) as a principal negative emission technology to reach climate change mitigation targets, but generally do not consider the possibility of C drawdown and soil organic C (SOC) sequestration from improved land management (*1*, *2*). Improved land management, without changing land use, may be an additional C sequestration option that does not require more land conversion. Land-use change and poor management practices have resulted in the loss of more than 130 Pg C from agricultural soil (*3*), leaving >1 billion hectares of degraded soil worldwide (*4*). Site-based studies and ecosystem-scale models have shown that degraded and managed agricultural lands have great potential to contribute to increased SOC sequestration through improved management (*5*–*7*). We define soil C sequestration as a net increase in SOC storage. Several agricultural (cropland and grazing land) management practices have been shown to increase soil C sequestration including organic amendments (*8*–*10*), cover crops, reduced tillage, improved crop rotations (*5*, *11*, *12*), and improved grazing management (*13*, *14*). Citing these proven practices and others, France and 33 other countries recently instituted a challenge to increase soil C by 4 per mil per year (*15*). However, the actual potential of these practices to contribute to lowering global temperature over time is poorly understood, despite recent efforts to quantify the amenable global land area and near-term sequestration rates associated with various practices (*16*–*18*). This is primarily due to uncertainty regarding the maintenance of soil C sequestration rates over time, the C sequestration capacity of different soils under different managements, and the sensitivity of global temperature changes to CO_2 emission and sequestration.

Here, we use a climate model emulator to translate SOC sequestration from agricultural management into a range of potential global mean surface temperature changes over time, consistent with global-scale outputs from the latest generation of Earth system models (ESMs; see Materials and Methods and fig. S1). Much of the research to date on the potential of land use–based SOC sequestration has focused on quantifying current sequestration rates with the implicit assumption that rates remain constant over time, often assuming a constrained time period of 20 to 50 years (*12*, *16*). The potential for SOC sequestration to contribute to a portfolio of mitigation strategies aimed at reducing climate change depends not only on the rates soon after C sequestering practices are implemented but also on the time-integrated dynamics of those rates, that is, how quickly land-use changes can be adopted, how long they remain in effect, and how SOC stocks change over time (*19*). This temporal dynamic is poorly understood but is critical to accurately estimate the potential for land-based management to slow climate change.

In practice, rates of SOC sequestration are likely to decline over time at any one site as soils reach new equilibria (*20*), but the time scale and shape of these declines are not well constrained by data and are likely to vary significantly among locations and management practices. To help bound this uncertainty, we model the effects of SOC sequestration on global surface temperature with and without consideration of effective sequestration years, defined as the number of years it would take to reach the maximum SOC stock (SOC max) at the current potential sequestration rate (see fig. S3). The SOC max is a concept proposed by Six *et al.* (*21*) and is poorly constrained by data at both site and global scales. An SOC max provides a theoretical limit on the amount of SOC storage in soils. As opposed to applying an arbitrary SOC max at a fixed time period (for example, 20 or 50 years), we model effective sequestration years as a continuum of time periods required to reach an SOC max (from 0 to 85 years) for a range of SOC sequestration rates. The current potential sequestration rate was taken from values reported in the literature (table S1). Our analysis focuses specifically on the temperature response to SOC sequestration. SOC storage is sensitive to a suite of global change factors such as elevated atmospheric CO_2 concentration and changes in climate, among others (*22*, *23*). These factors will likely have additional, albeit poorly constrained, impacts on management-induced SOC sequestration (*24*). Our goal here is not to quantify the ecological controls on SOC storage and loss in agricultural ecosystems but to determine the magnitude of SOC sequestration needed at a global scale to meaningfully affect temperatures and to explore the sensitivity of atmospheric temperature change to a range of possible temporal limits to soil C sequestration (effective sequestration years).

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RESULTS

The model shows that a global SOC sequestration rate of 0.68 Pg C year^{-1} from 2015 to 2100 would be required to yield a 0.1°C reduction in mean surface temperature in target year 2100 when coupled with an aggressive emission reduction scenario [Representative Concentration Pathway (RCP) 2.6; Fig. 1]. These results assumed a constant sequestration rate to the target year. The 0.68 Pg C year^{-1} global sequestration rate is at the low end of the ranges of published estimates, which vary from a low of 0.36 Pg C year^{-1} to a high of 1.56 Pg C year^{-1} (*12*, *17*, *25*, *26*). There is considerable uncertainty in the actual time horizon of soil C sequestration rates within sites, which is likely to vary in response to social, economic, and biophysical factors (*17*, *27*). Few studies have measured long-term (>20 years) patterns in soil C sequestration with agricultural management, and those have shown a wide range of continued sequestration rates from 20 to over 150 years (*11*, *28*–*30*). For this reason, we applied no a priori assumption on the time horizon required of soil C sequestration and, instead, modeled a continuum of effective sequestration years at SOC sequestration rates from 0 to 2.0 Pg C year^{-1}. It is important to note that, while the model assumes constant annual rates of SOC sequestration at a global scale, it does not require constant rates at individual sites.

Results were dependent on the underlying RCP scenario, assuming 3°C warming per doubling of CO_2. In scenarios with greater emission trajectories and thus higher atmospheric CO_2 concentrations (RCP 8.5 and RCP 6), greater SOC sequestration rates were required to reach the same reduction in global surface temperatures due to the logarithmic nature of CO_2 forcing (*31*). To achieve a 0.1°C reduction by the year 2100, the RCP 6.0 emission scenario would require a sequestration of 0.98 Pg C year^{-1}, while 1.25 Pg C year^{-1} would be required in the RCP 8.5 scenario. Management-based SOC sequestration had the highest efficacy in the RCP 2.6 scenario, indicating the importance of simultaneous emission reductions and SOC sequestration activities resulting from management. The sensitivity of climate to changes in atmospheric CO_2 concentration is a key uncertainty in the model and had a large influence on the temperature effect of C sequestration activities, as scenarios with lower climate sensitivity would require increased sequestration to result in the same temperature reduction (Fig. 1, black bars). Estimates of climate sensitivity range from 1.5° to 4.5°C warming per doubling CO_2, with a median estimate of around 3°C (*32*).

A synthesis of the literature yielded a mean annual SOC sequestration potential from agriculture of 0.83 Pg C year^{-1}, with an upper value of 1.78 Pg C year^{-1} (table S1). This value is greater than our estimate of 0.68 Pg C year^{-1} needed to reduce global temperatures by 0.1°C in 2100 under RCP 2.6 (Fig. 1), and results in a temperature reduction of 0.12°C in 2100 if sustained for 85 years. Greater SOC sequestration and associated temperature reduction may potentially be achieved with biochar amendments (see the Supplementary Materials); this approach is less well constrained than the other approaches and could require at least some utilization of abandoned lands (*10*, *33*), and is thus not considered further here.

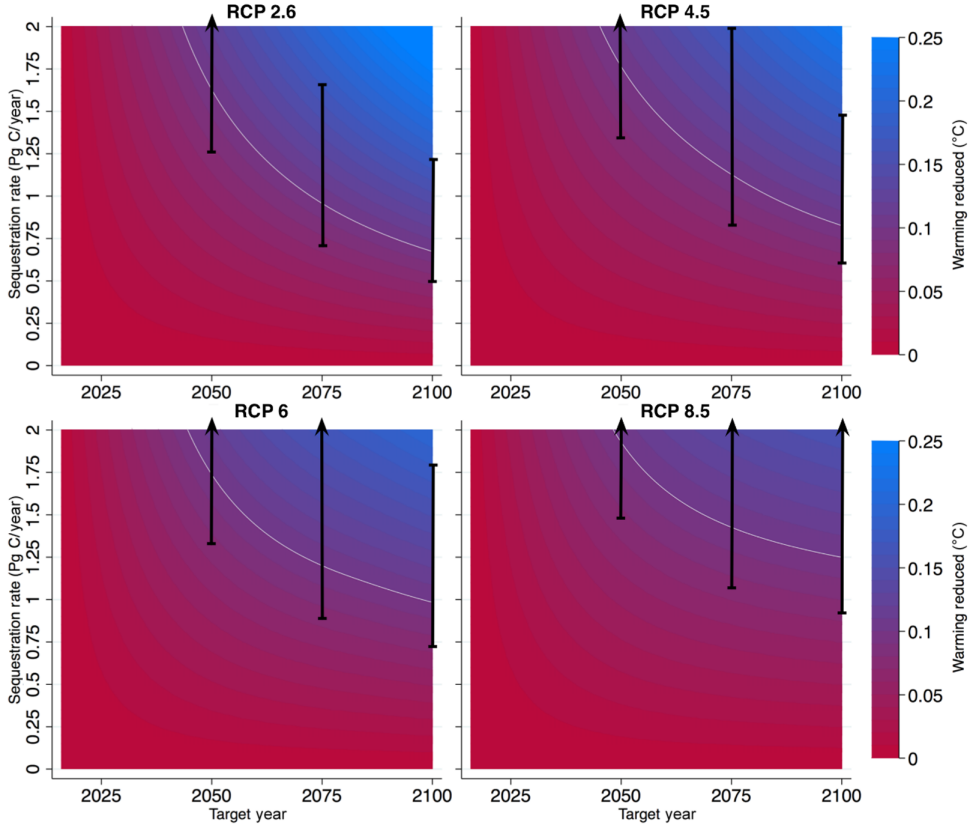

Fig. 1. Impact of constant global rates of C sequestration (Pg C year^{-1}) on mean surface temperatures by target year (2016–2100) for a climate sensitivity of 3°C per doubling of atmospheric CO_2. A 0.1°C reduction is highlighted by white lines. Different graphs indicate different RCP scenarios. Bars show the range of continued C sequestration rates needed to achieve a 0.1°C reduction in 2050, 2075, and 2100, respectively, under a range of alternative climate sensitivities from 1.5°C per doubling (upper bound) to 4.5°C per doubling (lower bound) (*32*). Upward arrows represent low CO_2 sensitivity upper bounds that are higher than the range of C sequestration rates (0 to 2 Pg C year^{-1}) considered in this study; error bars are not symmetric around the 0.1°C reduction line due to nonlinearities in CO_2 forcing.

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Uncertainties in potential global rates of SOC sequestration with improved land management can be partitioned into two primary factors: the range of field-scale SOC sequestration rates reported for each practice and the global land area over which the technique was considered effective. Both area and rate assumptions affect the estimate of total SOC sequestration potential. Area-dependent SOC sequestration rates varied from 0.02 to 1.15 Mg C ha^{-1} $year^{-1}$ through improved cropland management (*12*, *34*) and from 0.03 Mg C ha^{-1} $year^{-1}$ (*35*) to 0.62 Mg C ha^{-1} $year^{-1}$ through improved grazing land management (Table 1) (*10*, *26*). The range of amenable land area varied from approximately 2900 Mha for grazing land (*36*) to 400 Mha for cropland (*16*). We used the biophysical potential as the upper limit of SOC sequestration potential and the minimum reported SOC sequestration estimate as the lower limit (*16*, *17*, *37*). Nutrient availability at the field scale could theoretically limit SOC sequestration rates (*38*, *39*), although the increase in soil organic matter content can alleviate at least some of this limitation (*18*). We note that agricultural management to increase SOC storage can interact with soil inorganic C, by increasing storage or facilitating losses to the atmosphere (*40*). However, the long-term impacts of SOC sequestration on soil inorganic C dynamics are poorly understood. Economic constraints influenced the uncertainty regarding the amount of land amenable to improved management (*17*, *37*), as well as whether management strategies could be implemented quickly and maintained over multiple decades on the available and amenable land area. The management practices explored here are likely to simultaneously provide the co-benefit of improved soil fertility and water holding capacity, thus increasing the financial desirability for implementation.

The results were sensitive to effective sequestration years (Fig. 2), with the reduction in warming increasing roughly linearly with the number of years that soils could continue to sequester C. If we assume a limited effective sequestration period of 20 years (*11*, *28*), irrespective of the mechanism limiting C storage, then the climate impact in the year 2100 associated with a sequestration rate of 0.83 Pg C $year^{-1}$ decreased from 0.12° to 0.03°C under RCP 2.6. If the effective sequestration period is 50 years (*12*), then the climate impact in the year 2100 was 0.07°C under RCP 2.6. These values highlight the potential negative impact of short effective sequestration years. However, much of the world's soils are degraded with regard to SOC (*4*). Sanderman *et al.* (*3*) estimated that 75 and 133 Pg C have been lost globally from the top 1 to 2 m of soil, respectively, due to human land use. If we assume that the maximum soil C sequestration potential is equivalent to the amount of C that has been lost from soils due to land use, then soils globally would have the capacity to store an additional 0.9 Pg C $year^{-1}$ until 2100 in the top meter alone and 1.62 Pg C $year^{-1}$ in the top 2 m. To determine the impact of effective sequestration years on a given soil C sequestration rate from any combination of management strategies, we assessed the effect of the number of effective sequestration years (from 1 to 85) on the year 2100 global mean surface temperatures for the range of SOC sequestration rates (0 to 2.0 Pg C $year^{-1}$) previously considered (Fig. 2). In practice, SOC sequestration rates would likely exhibit a gradual decline over time, and the shape of this decline would likely vary by land use, climate, and soil type and is not well understood (*41*, *42*). Some studies have found that SOC stocks reach an asymptote over time (*28*). This can be indicative of the development of equilibrium conditions under a given rate of inputs (*11*). It has also been hypothesized that soils may become saturated with regard to SOC, with stocks ceasing to increase even at increasing input rates (*21*, *41*, *43*, *44*). Understanding of the long-term potential for soils to sequester C is limited, and mechanisms such as C stabilization and protection are not consistently represented in coupled climate–C cycle models and major ESMs (*45*). Our approach using effective sequestration years allows us to bound the uncertainty arising from these poorly understood mechanisms.

DISCUSSION

Our results show that existing management strategies on current agricultural lands have the potential to reduce global temperatures by the end of the century, sequestering as much as 1.78 Pg C $year^{-1}$. This rate of sequestration could result in warming reductions of as much as 0.26°C in 2100 (assuming an effective sequestration period of at least 85 years). These model results are dependent on the effective sequestration years at a global scale and concurrent trends in emission reduction. The time horizon of SOC sequestration is poorly understood but is critical for determining the long-term viability of these approaches. In particular, we note that climate change is a millennial-scale phenomenon that stretches beyond the 2100 target. Therefore, the residence time of organic C in soils, which can affect the long-term efficacy of SOC sequestration (*46*), is an additional concern. SOC has the potential to be stored for millennia [as evidenced by numerous radiocarbon studies (*47*, *48*)], particularly when considering the entire soil depth profile (*49*), but this may require a long-term commitment to maintaining soil C in the future.

Management-based soil C sequestration strategies were significantly more effective at reducing global warming under RCP 2.6 due to the atmospheric saturation of CO_2 in high emission scenarios (for example, in RCP 8.5). This result points to the value of combining aggressive emission reduction with C removal strategies for climate change mitigation. The management strategies we evaluated here are different from the measures assumed in the modeled RCP scenarios (*50*, *51*) and therefore provide additional negative emissions if applied simultaneously with emission reductions. The RCP scenarios can be realized through many alternative energy, land-use, and land-cover pathways, but current IAMs largely rely on land-cover change (for example, afforestation) and C capture and storage technology combined with bioenergy (BECCS) to reach goals of reduced radiative forcing (*50*). In contrast, this study examined the effects of improving management practices on agricultural

Table 1. Published global estimates of management amenable agricultural land and the C sequestration potential of land management techniques.

Management	Land type	Range of published amenable land area estimates (Mha)	Range of published potential C sequestration rates (Mg C ha^{-1} $year^{-1}$)	Sources
Improved cropland management	Cropland	380–1910	0.08–1.85	(*16*, *17*, *26*, *34*, *36*)
Improved grazing land management	Grazing land	500–2900	0.09–1.70	(*16*, *17*, *26*, *35*, *36*)

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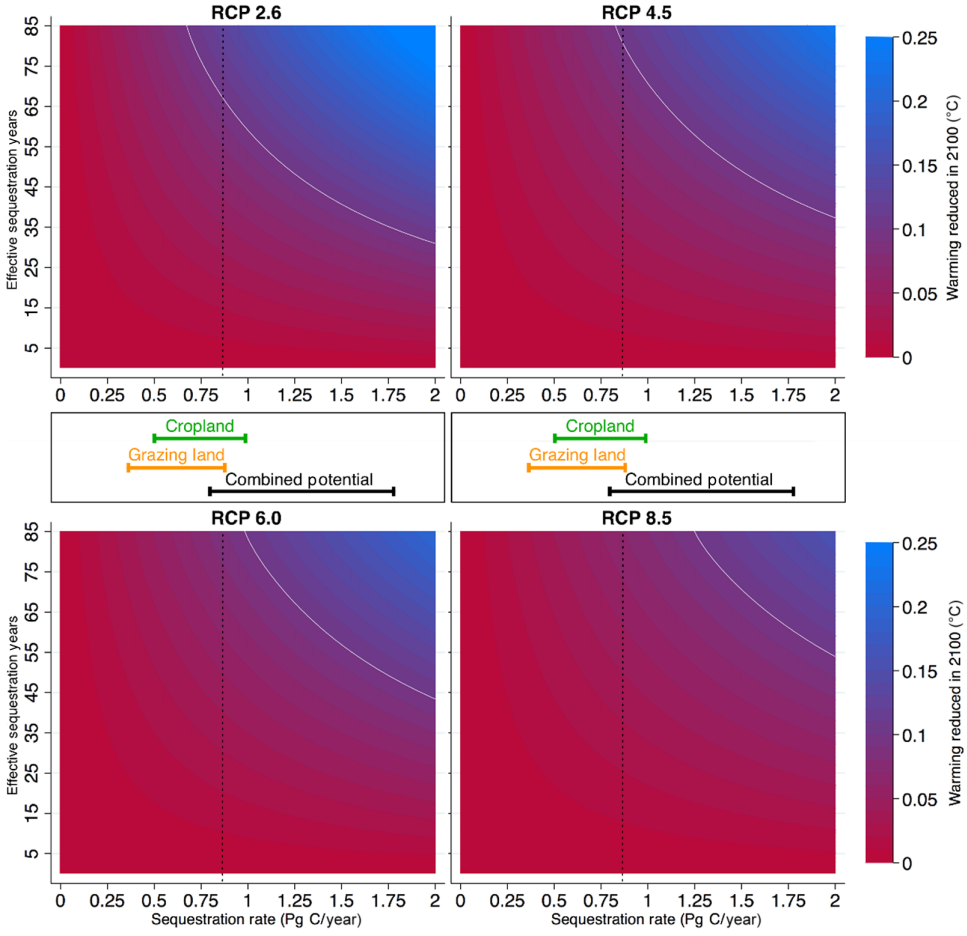

Fig. 2. Impact of SOC sequestration rate (Pg C year^{-1}) and effective sequestration years on 2100 global mean surface temperature for a climate sensitivity of 3°C per doubling CO_2 with a 0.1°C reduction (highlighted by a white line). A range of potential C sequestration rates are shown in the center of the chart, as well as their combined potential (black solid). The vertical dashed line shows the mean estimated potential of 0.83 Pg C year^{-1} for reference.

land currently in production. We note that future changes in the overall size of the agricultural land area will affect the area amenable to these practices and that heavy reliance on bioenergy could compete with some management activities on cropland or grazing land. This is one reason that we emphasize consideration of a large range of possible sequestration rates and time frames. Extensive adoption of land management strategies could moderately reduce the need for BECCS, which is considered extensively in most 1.5° and 2°C target scenarios (*52*). Sequestering an additional 1.78 Pg C year^{-1} through BECCS would require devoting 89 Mha of agricultural land to bioenergy production [equivalent to roughly half of current global maize area harvested (*53*)]. Growing bioenergy crops for BECCS on abandoned agricultural land could reduce the impact on food prices and ecosystem carbon storage (*33*), although lower crop yields and economic limitations on the use of abandoned lands must be accounted for in this context (*54*).

Our analysis also points to the importance of the long-term potential for SOC sequestration. The largely underappreciated scientific uncertainty of effective sequestration years greatly affected the climate change mitigation potential of land management strategies. A better understanding of the long-term regional potential of specific management applications for C sequestration, as well as the controls and limits on C sequestration, will facilitate better predictions of future land-atmosphere C cycle feedbacks and also inform the potential for long-term stabilization of C beyond the 2100 temperature target. As new strategies are identified for sequestering C through land management such as repurposing urban and rural nutrient and C waste streams (*7*, *55*), our model provides a framework for translating these into warming reductions.

MATERIALS AND METHODS

Climate model

We used a climate model that has been used previously in the literature (*56*–*59*) to evaluate the impact of emissions or emission reductions/C sequestration on future transient climate responses (fig. S1). The model takes a particular emission scenario for three major GHGs (CO_2, CH_4, and N_2O) and converts these emissions into atmospheric concentrations, radiative forcing, and transient temperature response. This emulator model has the benefit of enabling us to consider many possible permutations of sequestration rates and effective sequestration years while matching the global mean surface temperature response found in more complex ESMs such as those included in the Coupled Model Intercomparison Project 5 (CMIP5) featured in the Intergovernmental Panel on Climate Change 5th Assessment Report (IPCC AR5; fig. S1).

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As a single run of a coupled ESM would take 5 days, it would be prohibitively difficult to perform the 6800 separate combinations of sequestration rates and effective sequestration years examined in this paper.

To translate the rate of SOC sequestration into a transient global mean surface temperature response, we perturbed the emission scenarios in the RCPs by all possible sequestration rates between 0 and 3.0 Pg C year^{-1} from 2016 to 2100. We used simplified atmospheric lifetime functions for each GHG (*60*) to calculate both perturbed and unperturbed atmospheric CO_2 concentrations, translated these CO_2 concentrations into radiative forcing (*61*), and used a continuous diffusion slab ocean model to estimate transient temperature response (*62*). Reduction in warming associated with sequestration rates was calculated from the difference between the temperatures at a given point in time between the unperturbed and perturbed RCP scenario. We did not consider the potential effects of temperature change on SOC dynamics as this was beyond the scope of this study. These effects are poorly constrained, and different studies find both increases and decreases of the SOC stock with warming (*24*).

The model approximates the life cycle of each GHG using atmospheric lifetime functions adapted from Joos *et al.* (*60*). These model the percent of a discrete pulse remaining in the atmosphere after *t* years

$$G_{CO_2}(t) = 0.217 + 0.259e^{-t/172.9} + 0.338e^{-t/18.51} + 0.186e^{-t/1.186}$$
$$G_{CH_4}(t) = e^{-t/10}$$
$$G_{N_2O}(t) = e^{-t/114}$$

CH_4 and N_2O were assumed to have *e*-folding times of 10 and 114 years (for example, the time scale for a quantity to decrease to 1/*e* of its initial value), respectively, while CO_2 reflects more complex C cycle dynamics. These were converted into atmospheric concentrations $A_{gas}(t)$ by treating each annual emission (or emission reduction) as a discrete pulse and summing all pulse responses over the time period of interest *t*

$$A_{gas}(t) = \sum_{i=1}^{n} E_i G(t - t_i)$$

where E_i is the emissions in year *i* and $G(t - t_i)$ is the fraction of the gas remaining in the atmosphere after time $t - t_i$. The mass of each gas in the atmosphere was converted into concentrations in parts per million (ppm) [or parts per billion (ppb)] based on their respective molar mass.

The resulting atmospheric GHG concentrations closely mirror the results of CMIP5 runs (fig. S2) for the most part, although there is some divergence in high emissions (RCP 6 and RCP 8.5) scenarios where changes in ocean chemistry associated with acidification reduce the airborne fraction in a manner not captured by our emulator model. For this analysis, however, because we are looking at small perturbations in the net CO_2 emissions of underlying RCP scenarios, the limitations of the simple atmospheric carbon cycle model used should be minimal. We did not explicitly consider feedbacks or interactions between carbon sequestration and other GHG emissions (methane and nitrous oxide, in particular). These fluxes were poorly constrained for most of the land uses considered here, and thus, this was beyond the scope of the current analysis.

To convert atmospheric GHG concentrations into direct radiative forcing, we used the simplified radiative forcing functions from the IPCC AR5 (*61*). These are functional fits to more complicated absorption models derived from line-by-line radiative transfer functions that have relatively small uncertainties: about 1% for CO_2 radiative forcing and 10% for CH_4 radiative forcing calculations (*31*).

Forcing from a change in atmospheric concentration of CO_2 is given by

$$\Delta F_{CO_2} = 5.35 \cdot \ln \frac{(P_{CO_2} + \alpha_{CO_2})}{P_{CO_2}}$$

Here, P_{CO_2} represents the initial concentration of CO_2 in the atmosphere before the industrial era, while α_{CO_2} represents the additional parts per million CO_2 added for any given scenario. For the purposes of this analysis, P_{CO_2} was set to 277 ppm, the approximate value for the preindustrial era (for example, 1765).

The direct radiative forcing of a given increase of CH_4 and/or N_2O in the atmosphere can be approximated by (*61*)

$$\Delta F_{CH_4} = 0.036(\sqrt{P_{CH_4} + \beta_{CH_4}} - \sqrt{P_{CH_4}}) - f(P_{CH_4} + \beta_{CH_4}, P_{N_2O}) + f(P_{CH_4}, P_{N_2O})$$
$$\Delta F_{N_2O} = 0.12(\sqrt{P_{N_2O} + \beta_{N_2O}} - \sqrt{P_{N_2O}}) - f(P_{CH_4}, P_{N_2O} + \beta_{N_2O}) + f(P_{CH_4}, P_{N_2O})$$

where

$$f(M, N) = 0.47 \ln(1 + 2.01 \cdot 10^{-5}(MN)^{0.75} + 5.31 \cdot 10^{-15} M(MN)^{1.52})$$

In this equation, P_{CH_4} is the initial concentration of atmospheric CH_4, while β_{CH_4} is the addition being evaluated. P_{N_2O} is the initial concentration of N_2O, and β_{N_2O} is the addition being evaluated. The radiative forcing of both CH_4 and N_2O is a function of the combination of both, reflecting their interacting atmospheric chemistry. For this analysis, P_{CH_4} was set to 722 ppb and P_{N_2O} was set to 272 ppm, reflecting preindustrial atmospheric concentrations. $f(M, N)$ is a function that accounts for the interrelationship between CH_4 and N_2O forcing (*61*).

Radiative forcing was translated into a transient temperature response by using a continuous diffusion slab ocean model adapted from Caldeira and Myhrvold (*62*) and based on the study of Hansen *et al.* (*63*). It is governed by the equations

$$\frac{\partial \Delta T}{\partial t} = k_v \frac{\partial^2 \Delta T}{\partial z^2}$$
$$\left.\frac{\partial \Delta T}{\partial z}\right|_{z=0} = \left.\frac{(\lambda \Delta T - \Delta F(t))}{p f c_{p,w} k_v}\right|_{z=0}$$
$$\Delta T|_{t=0} = 0$$
$$\left.\frac{\partial \Delta T}{\partial z}\right|_{z=z_{max}} = 0$$

where *f* is the fraction of the earth covered by ocean (0.71), *p* is the density of water, c_p is the heat capacity of water, z_{max} is the maximum ocean depth (4000 m), λ is the feedback parameter ($\Delta T = \frac{\Delta F}{\lambda}$ at equilibrium, with λ =1.25 chosen to reflect a climate sensitivity of 3 C per doubling CO_2), and k_v is the ocean vertical thermal diffusivity (assumed

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to be 5.5×10^{-5} m^2 s^1). The land fraction of the earth was assumed to follow its equilibrium temperature response, with global surface temperatures being the area-weighted average of the two.

Literature analysis

We used published global estimates of C sequestration potential in grazing and croplands (table S1). Improved management approaches included conversion to reduced or conservation till (*12*, *17*, *64*), crop residue management (*64*, *65*), crop rotation and cover crop management (*12*, *17*, *66*), optimized irrigation and nutrient amendment strategies (*6*, *12*, *17*), biochar amendments (*10*, *16*, *26*), increased productivity of both cropland and grasslands (*6*, *12*, *17*), and improved grazing management (*17*, *25*, *26*, *35*, *67*). To better determine the impact of soil C sequestration on temperature, we used only estimates of soil C sinks, and not addition or avoidance of CO_2 emissions due to management. However, some global estimates account for nitrous oxide emissions stimulated or avoided due to management, and report C estimates in units of CO_2e or C equivalents. We therefore compared global estimates using the unit CO_2e-C, which was converted using the ratio of atomic mass: 1 Pg C = 12/44 × 1 Pg CO_2e. We reported estimates for biochar separately because of continuing interest in biochar as a means to sequester atmospheric CO_2 despite poorly constrained estimates of its persistence in soil and notwithstanding its potential land conversion requirements (*10*, *25*, *33*, *68*). Other management strategies, including compost and other organic amendments, could also be applied over large and diverse areas, but large-scale estimates for the potential of C sequestration from these strategies are lacking.

We differentiated between total soil C sequestration potential and the combined potential. Total C sequestration potential is an aggregation of literature estimates of the total global agricultural C sink potential (*12*, *17*, *25*, *26*, *37*). For the combined potential, we summed recent land-use and management-specific estimates for potential sequestration in cropland (*16*, *17*, *26*, *34*, *69*) and grazing lands (*16*, *17*, *26*, *35*, *69*) together with the available land area given in the same sources for these practices. We report this combined potential with and without biochar contributions, as biochar application can be used alone or coupled with other land-use practices for the same land area. Values given in the text are means ± 1 SE when multiple estimates were available.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/4/8/eaaq0932/DC1

Fig. S1. SimMod emulator climate model transient (solid red) temperature response compared to CMIP5 multimodel mean (black line) and 2.5 to 97.5% spread (gray area) for each RCP scenario.

Fig. S2. RCP (solid lines) and SimMod emulator climate model (dashed lines) atmospheric concentrations of CO_2, N_2O, and CH_4 for each scenario (*53*).

Fig. S3. A schematic illustration of the concept of effective sequestration years (ESY).

Fig. S4. Same as Fig. 2 in the text but with the inclusion of biochar and for a range of sequestration rates from 0 to 3 Pg C $year^{-1}$.

Table S1. Summary of global soil C sequestration potential (Pg C $year^{-1}$) by agricultural land management.

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Acknowledgments: We thank P. Smith for advice, support, and help with data interpretation. We also thank B. Collins for supporting the conception of the project, I. Fung for her challenge and friendly review, and J. Wick for encouragement. **Funding:** We thank the Rathmann Family Foundation for funding this project. This work was supported in part by the U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research under contract DE-AC02-05CH11231. **Author contributions:** A.M. contributed to conceptual development, conducted literature review, made figures, and led the writing effort. Z.H. contributed to conceptual development, updated and ran the carbon-climate model, made

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figures, and contributed to writing. A.D.J. and W.L.S. guided conceptual development and contributed to writing. W.L.S. conceived the project. **Competing interests:** The authors declare that they have no competing interests. **Data and materials availability:** The simple CMIP emulator model used in this analysis along with the underlying RCP scenario emissions are available on GitHub (https://github.com/hausfath/SimMod). All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Additional data related to this paper may be requested from the authors.

Submitted 29 September 2017
Accepted 23 July 2018
Published 29 August 2018
10.1126/sciadv.aaq0932

Citation: A. Mayer, Z. Hausfather, A. D. Jones, W. L. Silver, The potential of agricultural land management to contribute to lower global surface temperatures. *Sci. Adv.* **4**, eaaq0932 (2018).

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Science Advances

The potential of agricultural land management to contribute to lower global surface temperatures

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Sci Adv **4** (8), eaaq0932.
DOI: 10.1126/sciadv.aaq0932

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