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Integrated estimates of global terrestrial carbon sequestration

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Abstract

Assessing the contribution of terrestrial carbon sequestration to climate change mitigation requires integration across scientific and disciplinary boundaries. A comprehensive analysis incorporating ecologic, geographic and economic data was used to develop terrestrial carbon sequestration estimates for agricultural soil carbon, reforestation and pasture management. These estimates were applied in the MiniCAM integrated assessment model to evaluate mitigation strategies within policy and technology scenarios aimed at achieving atmospheric greenhouse gas stabilization by 2100. Terrestrial sequestration reaches a peak rate of 0.5–0.7 GtC yr^{-1} in mid-century with contributions from agricultural soils (0.21 GtC yr^{-1}), reforestation (0.31 GtC yr^{-1}) and pasture (0.15 GtC yr^{-1}). Sequestration rates vary over time and with different technology and policy scenarios. The combined contribution of terrestrial sequestration over the next century ranges from 23 to 41 GtC.
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Keywords: Climate change mitigation; Terrestrial carbon; Sequestration; Integrated assessment

1. Introduction

A large body of literature suggests that terrestrial sequestration of carbon through land management changes is an option for mitigating climate change. Analyses reviewed by the Intergovernmental Panel on Climate Change (IPCC) have estimated that about 38 Gigatons (Gt) of carbon could be sequestered over a 50-yr period by implementing afforestation, reforestation and agroforestry practices over 345 million ha of land (Brown et al., 1996). Likewise, 40 Gt of carbon could be sequestered in agricultural soil over a 50–100-yr span by applying improved agricultural practices (Cole et al., 1997). In many instances, there are also co-benefits (reduced soil erosion, reduced energy costs, improved soil fertility) that provide incentives for terrestrial sequestration practices.

Some terrestrial sequestration will occur regardless of the future policy environment. However, significant additional mitigation by terrestrial systems will occur only in the presence of a climate change policy that establishes prices and markets for carbon, as this paper will show. The adoption of terrestrial sequestration will be subject to competition with mitigation technologies as diverse as geologic sequestration, renewable energy and energy efficiency and its extent will be influenced by future land area allocation to food and biomass energy crops.

This paper considers the contribution of terrestrial sequestration toward greenhouse gas stabilization by 2100 within a multi-sector approach. A new global analysis of terrestrial carbon sequestration potential in agricultural soils, based on detailed soils and geographic data, has been developed. This, along with estimates of reforestation and carbon sequestration in pasturelands, was linked with the land-use module of the MiniCAM integrated assessment model to develop a set of stabilization scenarios based on differing assumptions about energy technology evolution over the coming century. Two sets of assumptions were used to better understand the implications of increasing technological opportunities. By linking terrestrial carbon sequestration options with a formal integrated assessment model, the contribution to greenhouse gas mitigation can be realistically assessed and compared to the contributions of options in the energy sector.

While terrestrial sequestration options have been previously integrated into scenario analyses using MiniCAM

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(Placet et al., 2004), these estimates were not developed from specific physical assumptions. Here we use global agricultural, soil and land-use data to establish estimates of terrestrial carbon sequestration that can be applied in MiniCAM for a suite of climate change technology and stabilization scenarios. This establishes methodologies for global terrestrial sequestration estimates compatible with MiniCAM, improves the dynamics of terrestrial sequestration in the scenarios, provides realistic estimates of mitigation potential, and identifies the data and research requirements for inclusion of global, geographically distributed terrestrial sequestration estimates into integrated assessment models.

2. Methods and data analysis

2.1. Overview of the scenario analysis

The work described in this paper was conducted as part of a broader scenario analysis exploring the role of advanced technology in stabilizing atmospheric greenhouse gas concentrations as part of the Climate Change Technology Program (Clarke et al., 2006). The scenario analysis compared the energy, emissions, and economic implications of three distinct sets of advanced technology model assumptions with a set of reference technology assumptions that included continued, but less optimistic, improvements in technology. These four sets of technology assumptions were compared in the context of stabilizing the long-term, combined radiative-forcing effects of carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and a set of fluorine-containing industrial chemicals known as F-gases. Four stabilization levels were explored with the technology assumptions, leading to CO_2 concentrations of roughly 450, 550, 650 and 750 parts per million of CO_2 by volume (ppmv). A baseline scenario using reference technology assumptions, but with no constraint on CO_2 emissions, was also constructed.

Two sets of terrestrial sequestration assumptions were used in the analysis: reference technology and advanced technology. The same terrestrial sequestration assumptions were used in all of the advanced technology scenarios, whereas many energy sector assumptions differed across the advanced technology scenarios. All components, except terrestrial sequestration, were developed using MiniCAM and linked through land-use distributions and carbon prices. One additional iteration provided acceptable convergence between the terrestrial sequestration calculations and MiniCAM. Terrestrial sequestration options explored in the analysis included (1) sequestration in agricultural soils, (2) reforestation of currently unforested land, and (3) sequestration in pasturelands.

2.2. Overview of MiniCAM

MiniCAM is an integrated assessment model, a tool for exploring the complex interrelationships among economic activity, the energy and industrial system, managed and unmanaged ecosystems, the associated greenhouse gas emissions, and the resulting impacts on climate. MiniCAM generates results over a century-long time scale. The model has its origins in the ERB model (Edmonds and Reilly, 1985) and has been continually refined to allow for substantial focus on technology and the implications of technology for emissions mitigation (Edmonds et al., 2004; Brenkert et al. 2003). The version used here has a structure based in C^{++} (Kim, et al. 2006).

MiniCAM models the energy and industrial system, including land-use, in an economically consistent global framework for 14 world regions[1] in 15-yr time steps. As a partial equilibrium model, MiniCAM explicitly models specific markets and solves for equilibrium prices only in its areas of focus (energy, agriculture and other land-uses, and emissions). Population and labor productivity growth rates are provided as assumptions to the model.

Because of the importance of land-use in the emissions and sequestration of greenhouse gases, as well as the interaction between land-use and biofuels, MiniCAM includes a land-use module to represent the competition between differing uses of land; food and biomass energy crops, pasture, managed forests, and unmanaged lands. This module provides land-use changes and an estimate of the resulting net emissions from deforestation. In climate policy scenarios, higher demand for biomass fuels can provide artificial incentive for deforestation (Sands and Leimbach, 2003). In these scenarios an adjustment was made to biomass energy prices to provide a value for carbon in undisturbed ecosystems, thereby accounting for avoided deforestation (Clarke et al., 2006).

2.3. Soil carbon sequestration

2.3.1. Approach and data analysis

Changes in soil carbon under no-tillage (NT) practices are assumed to follow first-order kinetics (soil carbon decomposition is proportional to the first power of the carbon content in soil) with the addition of residues (Smith, 2002). Mathematically:

$$\frac{dC}{dt} = -kC + A, \tag{1}$$

where C is the soil carbon content ($\mathrm{Mg\,C\,ha^{-1}}$), t the time (y), k the decay rate ($\mathrm{y^{-1}}$), and A the rate of addition of residues ($\mathrm{Mg\,ha^{-1}\,y^{-1}}$).

Since soil carbon compounds are not homogenous with respect to their rate of decomposition (some carbon compounds are more (less) labile than others), the total carbon pool is divided into three pools; C_1, associated with crop/root residues, C_2, active, and C_3, passive. The analytical solution of this equation is presented by

[1]MiniCAM Regions: United States, Canada, Japan, Western Europe, Eastern Europe, Former Soviet Union, Africa, Latin America, China, South and East Asia, India, South Korea, Middle East, and Australia–New Zealand.

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Izaurralde et al. (2001) as

$$C_t = F_1 C_t e^{-k_1 t} + \frac{A_t R_1}{k_1}(1 - e^{-k_1 t}) + F_2 C_t e^{-k_2 t} + \frac{A_t R_2}{k_2}(1 - e^{-k_2 t}) + F_3 C_t e^{-k_3 t} + \frac{A_t R_3}{k_3}(1 - e^{-k_3 t}), \quad (2)$$

where C_t is the soil carbon content ($\mathrm{Mg\,C\,ha^{-1}}$) at time t (yr); $C_1 + C_2 + C_3 = C_t$; F_1, F_2, F_3 the fraction of original (t_0) soil carbon in each compartment; $F_1 + F_2 + F_3 = 1$; k_1, k_2, k_3 the specific decay rate ($\mathrm{yr^{-1}}$); A_t the annual additions of carbon ($\mathrm{Mg\,C\,ha^{-1}\,yr^{-1}}$); R_1, R_2, R_3 the fraction of the added carbon that is partitioned to each compartment; $R_1 + R_2 + R_3 = 1$. Values of C_t for conventional and NT are calculated at 15-yr time steps, compatible with MiniCAM. Carbon sequestration amounts as a function of time are calculated as

$$\Delta C = \frac{C_t(t_2) - C_t(t_1)}{y}. \quad (3)$$

Decay rate constants (k) are constant only for a given set of biotic and abiotic conditions (Smith, 2002). Values for initialization of these components (Table 1) are similar to those fitted by Izaurralde et al. (2001) using non-linear statistical procedures for a long-term experiment. These parameters result in a mean residence time (MRT) value of 65 yr ($k = 0.016$) for whole soil, similar to average MRT values synthesized by Six and Jastrow (2002) for a series of sites using first-order modeling (67 ± 12 yr, 7 sites) and ^{13}C abundance methods in cultivated systems (61 ± 9 yr, 20 sites).

To incorporate sequestration estimates into a global model, they must be based on data that are available globally to the same standard. Therefore, the soil carbon content of each region under current practices was determined using FAO soil orders classified globally into a gridded data set by Zobler (1986). The organic carbon content and bulk density of each soil order to 30 cm depth was taken from an analysis by Batjes (2002) of over 9600 soil profiles. GIS analysis determined the coverage of each soil order in each of the 14 MiniCAM regions. The agricultural land area of each soil order within each region was adjusted based on the global croplands data set of Ramankutty and Foley (1998) to produce initial carbon content for soils. We assume that soil orders with the largest fraction of cropland are major agricultural soils that have historically been under conventional cultivation.

Table 1
Initial allocation of soil carbon compartments (C_i), fraction of carbon inputs (R_i), specific decay constants (k_i)

	C_1 (crop/root residues)	C_2 (active)	C_3 (passive)	Carbon (whole soil)
F_i	0.05	0.45	0.5	1.00
R_i	0.85	0.10	0.05	1.00
k_i ($\mathrm{yr^{-1}}$)	0.2	0.01	0.002	0.016
MRT_i (yr)	5	100	500	65

The additions of residue to the soil (A) were calculated based on FAO crop yield data for each region for major grain crops (FAO, 2005) using straw yield calculations based on crop harvest index. The fraction of agricultural land in each crop in the major regions was used to determine residue inputs. We assume that crop yields for a given region implicitly express the influence of abiotic (e.g., precipitation, temperature), biotic (e.g., soil conditions, genetic characteristics), and management (e.g., fertilizer and other inputs) factors on crop productivity and thus on carbon inputs.

MiniCAM provided regional agricultural land area at each time step. Only areas for grain and oil crops were considered for potential application of NT practices. Crop land where NT practices are not likely, such as rice, root, fruit, and vegetables was excluded. The annual rate of carbon sequestration was calculated from the result of conversion to NT for each region.

2.3.2. Soil carbon sequestration adoption

Soil carbon in the stabilization scenarios is controlled by the adoption rate of sequestering practices and the maximum potential adoption as determined by the carbon price in each scenario (Fig. 1). Initial adoption was determined by country weighted analysis of land area in NT (Derpsch, 2005). The adoption rate was calculated under the assumptions that a higher carbon price will increase both the rate of adoption and the land area available for adoption. The adoption of technological innovations was represented with an S-shaped (or logistic) curve of the form:

$$A_f = \frac{A_m}{1 + A_m/A_b - 1)e^{-rt}}, \quad (4)$$

where A_f is the adoption fraction at time t, A_m the maximum adoption of soil carbon-sequestering practice, A_b the base adoption, and r the rate of adoption. Similar to the adoption of technological innovation, Easterling et al. (2003) used this type of equation to describe how farmers would make agronomic adaptation in response to climate change.

We also made the rate of adoption r sensitive to a price modifier, under the assumption that a rising (or falling) carbon price could accelerate (or decelerate) the adoption of a soil carbon-sequestering practice:

$$r' = re^{bP}, \quad (5)$$

where r' is the price-dependent rate of soil sequestration adoption, r the rate of adoption, b the modifier of price, estimated at 0.01, and P the carbon price ($).

The adoption of NT over all agricultural lands worldwide is not likely due to the heterogeneity of soil properties, the availability of knowledge and equipment to implement NT, and potential changes in crop production. To account for this, the soil carbon sequestration from Eq. (5) was

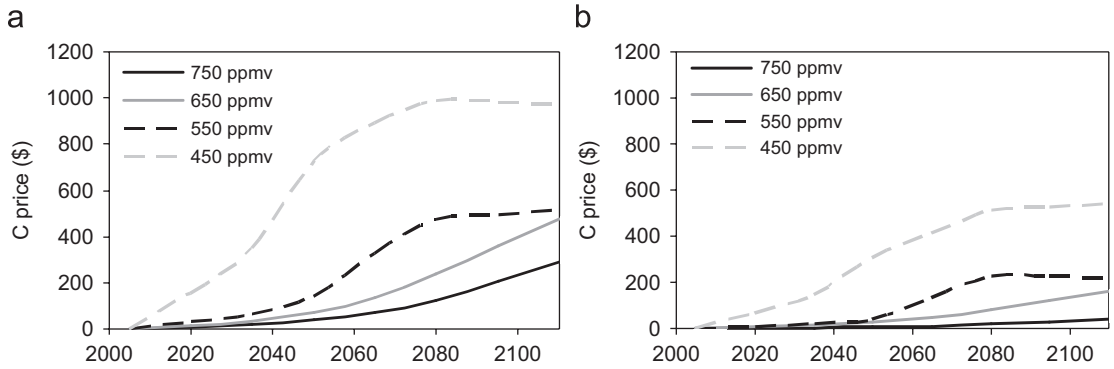

Fig. 1. Carbon price for each stabilization scenario under (a) reference and (b) advanced technology scenarios.

Table 2
Percentage of total agricultural land in each MiniCAM region under no tillage in the initial period and under the maximum assumptions used in Eq. (5)

Region	Initial (A_b)	Maximum (A_m)
United States	13.5	68.8
Canada	29.3	70.0
Western Europe	1.5	69.0
Japan	1.0	12.3
Australia–New Zealand	18.6	69.6
Former Soviet Union	1.0	69.5
Eastern Europe	1.0	69.9
Latin America	44.6	61.2
Africa	1.0	61.0
Middle East	1.0	65.8
China	1.0	42.6
India	1.0	38.1
South Korea	1.0	6.8
Southeast Asia	3.0	20.7

adjusted based on the marginal abatement cost curves for the economic potential of soil carbon sequestration as reported in McCarl and Sands (2007). The initial adoption and maximum adoption fractions, as percentage of total agricultural land in each MiniCAM region, are given in Table 2. In some regions such as Latin America, NT is currently practiced over more than 40% of cropland, while in the majority of regions, including regions in Europe and Asia, NT is practiced on only 1% of available cropland. Maximum adoption fraction assumes an upper bound of 70%, which is reached in grain-producing regions such as the United States, Canada, and the Former Soviet Union, with lower potentials in regions with high proportions of rice or root crops, such as South Korea, India, and China.

Estimates from the reference case show an initial soil carbon sequestration rate of 28 TgC yr^{-1} for the United States in the first time period (2005) before consideration of the competition from other mitigation technologies in MiniCAM. This can be compared to historical estimates by Pacala et al. (2001) of 7 TgC yr^{-1}, Eve et al. (2002) of 21.2 TgC yr^{-1}, Sperow et al. (2003) of 8.2 TgC yr^{-1}, and Ogle et al. (2003) of 6.9 TgC yr^{-1} from the 1980s and 1990s. Soil sequestration rates reach a maximum of 200 TgC yr^{-1} by the end of the century in this analysis while literature projections indicate future potential sequestration of 40–208 TgC yr^{-1} (Lal et al., 1998; Sperow et al., 2003). The maximum sequestration level reached in the later periods of this study fit well with the maximum projected by Lal et al. (1998), which includes some additional practices not considered here. Therefore our analysis may be overestimating the sequestration potential of a change in tillage only.

2.3.3. Advanced technology assumptions for soil carbon sequestration

We assume that the reference technology cases will implement existing technology as represented by the above calculations. Sequestration potential of the advanced technology scenario was determined by varying two biophysical soil carbon factors (see Section 2.3.1). An increase of 30% was applied to the carbon additions to soil (A in Eq. (1)), which reflects the assumption of technologies that improve crop yields, increase fertilization, improve residue management and develop high-yielding crop varieties. The other potential advanced technology impact on soil carbon sequestration is an increase in the maximum amount of carbon that can be stored in the soil. This was represented by a decrease of 10% in the decay rate coefficient (k), which increases the mean residence time of carbon in the soil and therefore increases the quantity of carbon in the soil at any given time. These assumptions represent the potential development of technologies such as deep soil carbon storage, soil amendments or manipulations of soil microbial communities (Post et al., 2004). These assumptions of advanced technology increase the potential rate of sequestration by up to 20% (Fig. 2) in mid-century.

2.4. Carbon sequestration through reforestation

Increasing the carbon in forests is another way of reducing atmospheric CO_2 concentrations. Forestry activities can be divided into reforestation, afforestation, avoided deforestation, and changes in forestry management

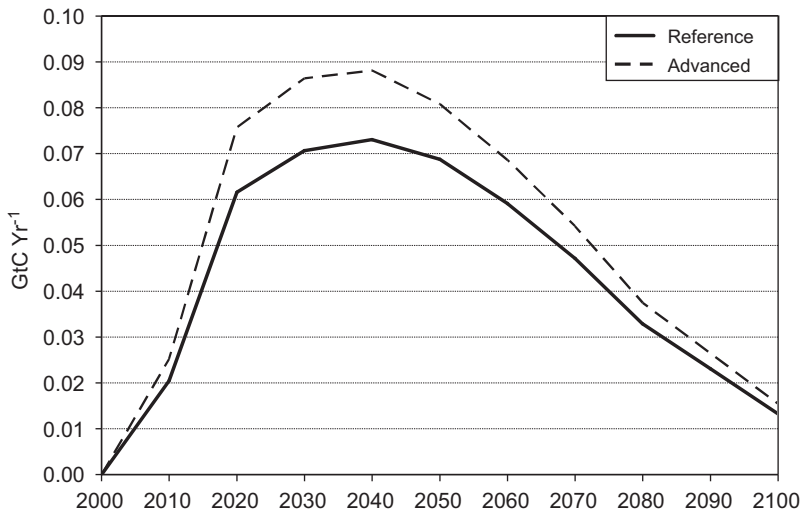

Fig. 2. Soil carbon sequestration rates over the simulation period with no carbon policy under base and advanced technology scenarios.

practices.[2] "*Afforestation* and *reforestation* both refer to establishment of trees on non-treed land. Reforestation refers to establishment of forest on land that had recent tree cover, whereas afforestation refers to land that has been without forest for much longer" (Watson et al., 2000). The calculations here consider afforestation, the reestablishment of forests on land that is not currently forested. Avoided deforestation is treated endogenously within MiniCAM (Clarke et al., 2006).

The amount of land that could be potentially reforested was estimated using gridded data sets to determine the extent of lands not currently forested or otherwise managed intensively, but where forest cover could naturally occur. Current forest cover was taken from DeFries et al. (2000), obtained from (UNEP, 2006), potential forest cover and current arable land from Ramankutty and Foley (1999), and pasture and built-up land area from Foley et al. (2003).

The calculations were performed on a 0.5° grid with potential vegetation and forest cover data sets aggregated from 5 min data. The forest cover data set has a maximum value of 80%, due to limits in the satellite data-processing algorithm. Since these areas could be already maximally forested, areas with aggregated (0.5°) forest coverage of 75% or greater (primarily in South America and Africa) are excluded. To produce a conservative estimate, arable land, pastureland, and currently built-up land are not considered for reforestation. Due to inconsistencies in data, boreal regions, as defined through Global Agro-Ecological Zone (GAEZ) calculations from Lee et al. (2005), were also removed from the calculation.

In order to translate reforested area into carbon sequestration scenarios, we use aboveground forest carbon content and forest re-growth rates from Houghton and Hackler (2001). This implicitly assumes that re-growth is of vegetation similar to the natural vegetation native to a given region. We return to this point in the discussion of results.

The areas of potential reforestation determined above were further reduced by the fraction of forest reduction over time in each region reflecting potential conversion of these areas to other uses. For example, forest area overall decreased by 32% by 2100 in Africa in the reference scenario through conversion to crops, biomass and pasture. The areas that could potentially be reforested are assumed to be influenced by the same land-use changes. The area available for potential reforestation was, therefore, also reduced by 32% in Africa. This adjustment reduced areas by 35% globally. Additionally, increases in population were assumed to encroach into potentially forested areas, although this adjustment is small globally.

The reference technology assumption is that one-third of the area thus determined can be reforested. The remaining areas are assumed to be valued for other purposes, would have been reforested even without climate policy (although this is not included in the scenarios), or somehow unsuitable or too degraded to be restored.

For the advanced technology scenario, the assumed fraction of area that can be reforested is increased to 40%. These fractions are chosen to provide a conservative estimate as it is certain that not all areas that could potentially be reforested would be returned to forest as there will be other uses for this land. The true global potential for reforestation is not well known, particularly given competing uses for land. More detailed consideration of these constraints is warranted.

Re-growth of forests may also increase the amount of carbon in soils. The net amount of carbon sequestration would depend on the current level of soil carbon in potential afforestation sites. In order to be conservative, changes in forest soil carbon are not considered in this calculation.

[2]Carbon storage through forestry practices changes can have a large impact, but are not directly considered here.

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Reforestation in the stabilization scenarios is only considered when it occurs due to the presence of a climate change policy. While reforestation occurs due to considerations other than climate change, such as ecosystem preservation and land-use change, no additional reforestation is included in the baseline. Baseline land-use changes, including reforestation, are already included in the model carbon-cycle calculations. In the stabilization scenarios, the reforested area in each region was assumed to be planted over a 30-yr period. Forests were taken to exponentially approach their maximum above ground carbon density using the time scales from Houghton and Hackler (2001). While these re-growth timescales are presumably broadly applicable to the regions indicated, more spatially explicit estimates of forest re-growth would be desirable since forest characteristics can vary significantly within a region.

The stabilization scenarios differ in terms of when the planting is initiated. Reforestation is initiated only when the value of carbon reaches \$10 Mg^{-1}. Hence, the more stringent the carbon constraint, the earlier that reforestation begins. This is a larger price signal than is required for sequestration in agricultural soils and pasture, because economic benefits are associated with soil sequestration even without constraints on carbon. Therefore reforestation begins later than the other two terrestrial sequestration options. In the stabilization scenarios at high atmospheric CO_2 (750 ppmv), reforestation does not begin in earnest until after mid-century. Reforestation sequestration also attenuates more rapidly from its peak than sequestration in agricultural soils and pasture (Figs. 3 and 4).

2.5. Carbon sequestration in pasturelands

Terrestrial carbon sequestration options for grasslands include converting grasslands to forest, or increasing the productivity and/or carbon content of managed grasslands (Conant et al., 2001; Post and Kwon, 2000). A review of the literature indicates a wide range of potential enhancements; however, substantial uncertainty exists in the amount of pastureland to which these enhancements could be applied. Some of these options involve management changes such as increased fertilizer applications, which would result in higher N_2O emissions and therefore increase net greenhouse gas emissions.

Only enhanced sequestration on pasturelands were considered in these scenarios; unmanaged grasslands were not considered. The pastureland areas as used in the MiniCAM model (derived from FAO data) were used as the basis for pastureland carbon sequestration. These data represent permanent pasture, which is presumably already under management. A century-scale potential for terrestrial sequestration in pastures was developed associated with stabilization at 550 ppmv. For the remaining three stabilization scenarios, this total was adjusted based on the

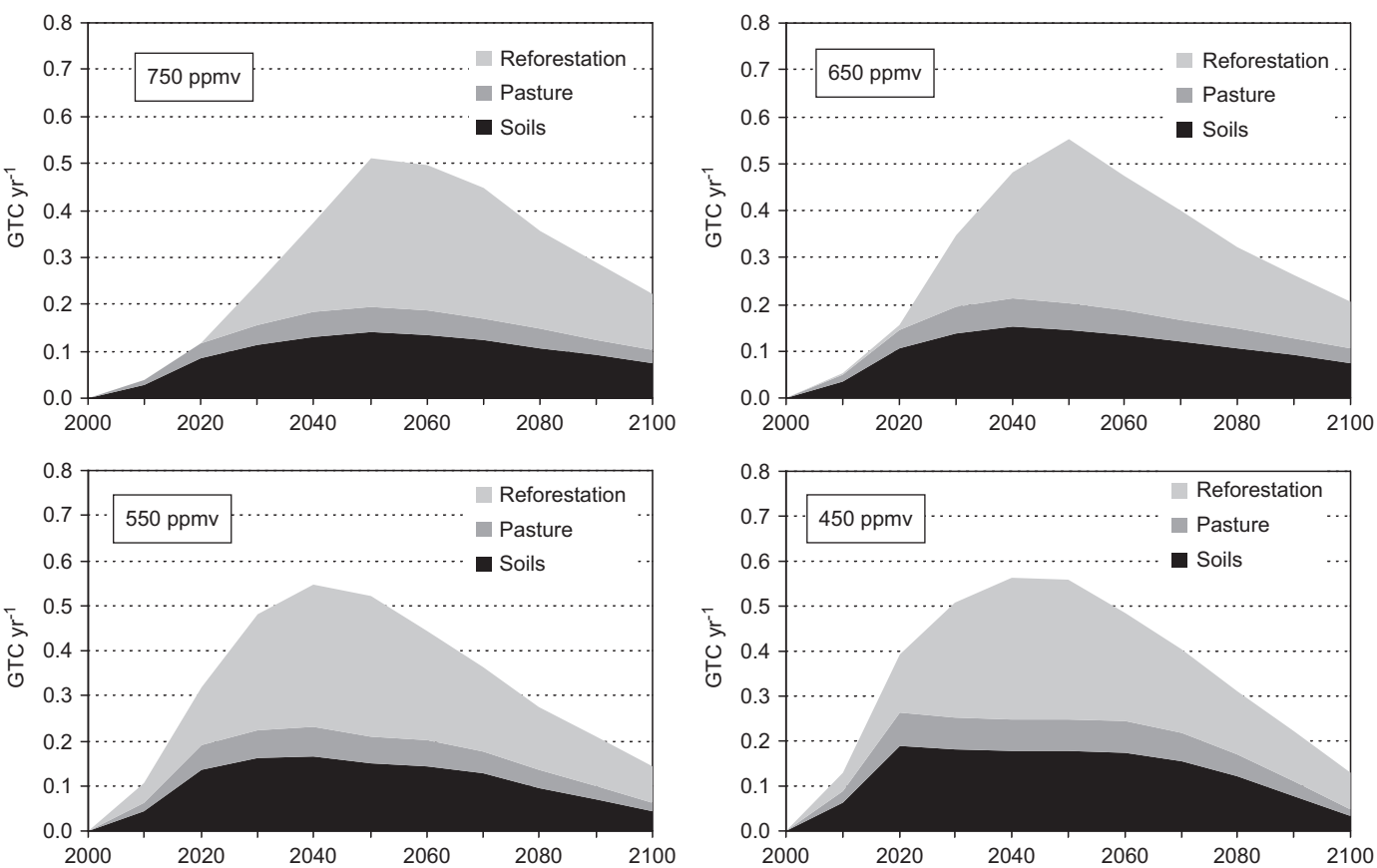

Fig. 3. Contribution of terrestrial carbon sequestration to greenhouse gas mitigation under four climate policy levels using base technology assumptions.

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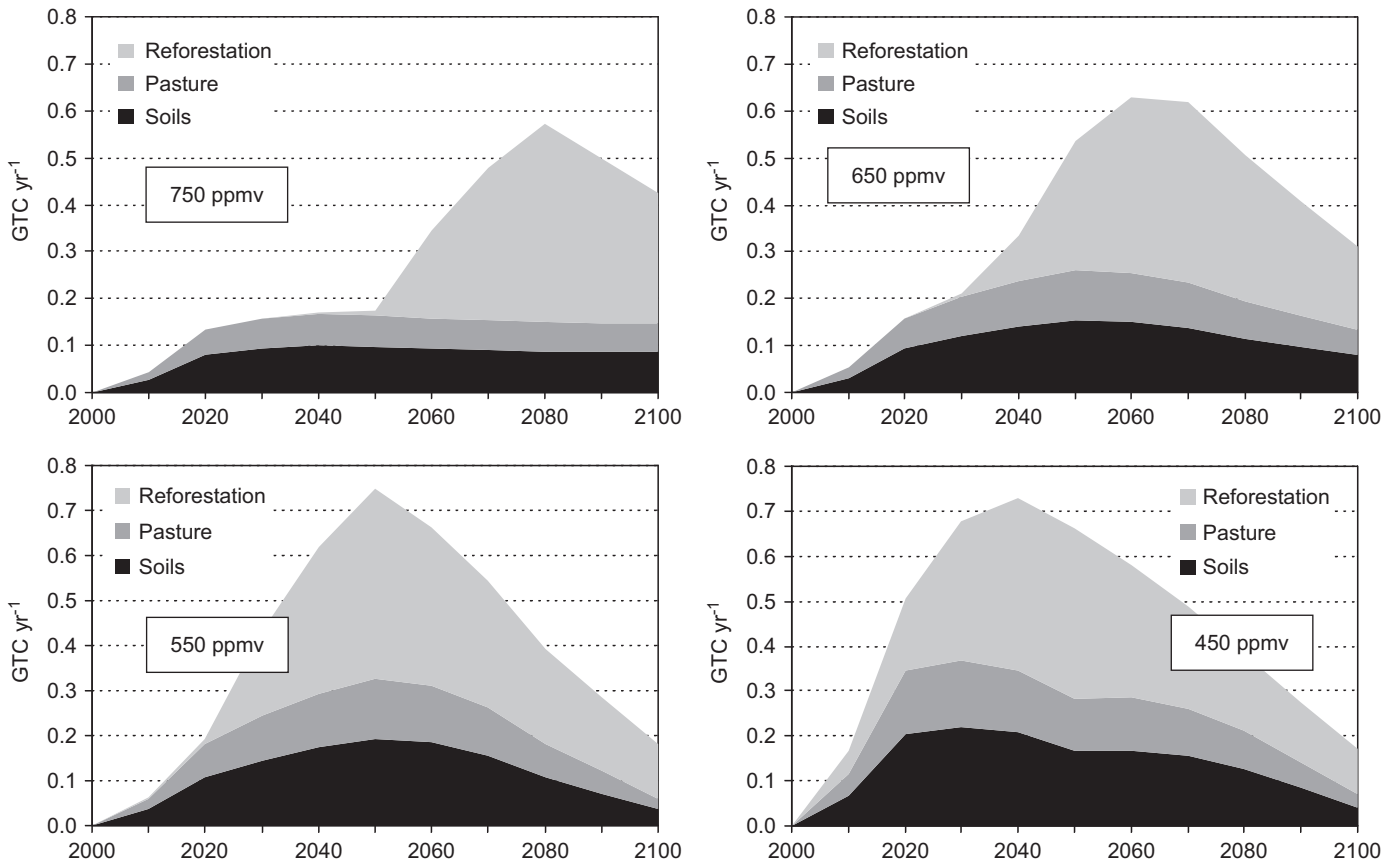

Fig. 4. Contribution of terrestrial carbon sequestration to greenhouse gas mitigation under four climate policy levels using advanced technology assumptions.

percentage variations in the totals associated with agricultural soil carbon. The time path was also assumed to follow the time path for agricultural soils. Terrestrial sequestration in pasturelands differs from that in agricultural soils, however, in that no sequestration is assumed in the baseline scenario in the former, while sequestration in agricultural soils occurs without constraints on carbon emissions.

Note that conversion of pasture to forested land is not considered in these scenarios. At a sufficiently high carbon price there are likely to be some pasturelands that are suitable for reforestation and such conversions would be economically attractive, although land quality and competing demands for beef and other meat products would need to be taken into account.

3. Results and discussion

Figs. 3 and 4 show total terrestrial sequestration for the four stabilization targets, corresponding roughly to atmospheric CO_2 concentrations of 450, 550, 650, and 750 ppmv in 2100. With the advanced technology assumptions and strictest stabilization level (450 ppmv), the cumulative sequestration by the end of the century is similar for reforestation and agricultural soils and slightly smaller for pasture management. Agricultural soils provide a large share of emissions mitigation early in the century, indicating that these technologies can be rapidly expanded under a climate policy. In contrast, additional sequestration with reforestation is delayed by the need for a stronger price signal, yet toward the mid-point of the century forestry contributes carbon to terrestrial stocks at double the rate of pasture and soil sequestration.

3.1. Soil carbon in agricultural lands

Agricultural soil carbon sequestration rates increase over the first 50 yr as a result of increasing price incentives (Figs. 1 and 2). Total potential sequestration from soil carbon ranges from 0 to 0.07 Gt C yr^{-1} in the reference scenario, representing a baseline level of soil carbon sequestration practice adoption. Soil carbon sequestration adoption occurs quickly as carbon prices are introduced in the first time step, while a stronger price signal is necessary for the adoption of reforestation (Figs. 3 and 4). Adoption and peak potential soil carbon sequestration is highest under the strict 450 ppmv target where carbon price exceeds \$150 ton^{-1} by 2020, an illustration of the early adoption of soil carbon sequestration that is possible, but nevertheless not likely to occur without a price signal. In addition, at 450 and 550 ppmv stabilization, sequestration is maintained at a higher level in the second half of the century, indicating that the more stringent target

both induces carbon sequestration efforts sooner and encourages continued adoption.

Soil carbon sequestration rates are slightly higher in the advanced technology scenarios (Fig. 4) with a peak of over 0.2 GTC yr^{-1} with stabilization at 450 ppmv. Under advanced technology, the difference between the no policy and stabilization at 750 ppmv is much smaller than under the reference scenario due to much lower carbon prices throughout the century in the advanced case (Fig. 1). Total cumulative carbon stored in soils over the century ranges from 9 Gt with stabilization at 750 ppmv to 19 Gt with stabilization at 450 ppmv. These quantities are substantially lower than the 40 Gt estimated by Cole et al. (1997), a difference that is attributable in part through our consideration of only one agricultural practice, NT, and the parameters determining rate of adoption established by Eqs. (4) and (5) above.

3.2. Reforestation

The total global area available for reforestation was conservatively estimated to be 570 million ha. Reforestation of all of this area would eventually result in 120 GtC of above ground carbon assuming natural regeneration of forests. Land-use changes over the next century reduce this maximum sequestration amount to 80 GtC. The reference technology assumption of use of one-third of the potential area results in a maximum sequestration rate of 0.26 GtC yr^{-1} (Fig. 3) with an ultimate total carbon sequestration of 26 GtC on 120 million ha. Under the advanced technology scenarios, the maximum rate of forestry sequestration reaches 0.31 GtC yr^{-1} (Fig. 4).

Comparing to other results in the literature, Winjum and Dixon (1992) use a forest land database to estimate 1000 million ha of land available for reforestation in tropical and temperate regions, or about twice the value of the calculation conducted here. Nilsson and Schopfhauser (1995) estimate 345 million ha sequestering 104 GtC over 100 yr, with 80 GtC above ground. This is very similar to the estimate here for the same land area. This similarity masks a significant difference in assumptions, however. The timber yield-based calculations of Nilsson and Schopfhauser (1995) result in a large rate of carbon sequestration even after 100 yr, while the ecosystem parameters taken from Houghton and Hackler (2001) imply that carbon uptake has slowed significantly by this time. This is a significant difference in assumed forest dynamics and needs to be investigated further. This may also indicate a difference between the dynamics of a natural forest ecosystem and a managed forest or assumptions about long-term forest heterogeneity.

The land area dedicated to the production of forest products is substantially larger than the area available for reforestation. Changes in forestry practices such as changes in rotation length or species selection could potentially also result in additional terrestrial carbon storage. In addition, when currently unforested areas are converted to managed forestry there can be a two-fold benefit: enhanced carbon content of the reforested areas and avoided deforestation of areas that might otherwise have been logged for forest products.

Benítez et al. (2007) determine that from 2600 to 3500 million ha could be reforested and used to produce forest products, a figure far larger than the area estimated here. The calculations were based on a combination of economics and land constraints, with highly productive and populated areas excluded but low productivity agricultural land considered available for reforestation. The amount of agricultural land that could be potentially used for reforestation is not clear given the near certain expansion of food demands over the next century. One estimate is given by van Vuuren et al. (2007), who find that under a climate policy from 725 to 940 million ha of abandoned agricultural land could be converted to forestry, potentially sequestering 116–146 GtC by 2100.

Sohngen and Mendelsohn (2003) find an additional 400–960 million ha of forested land by 2100 (including boreal regions). Carbon sequestration for their two cases ranges from 40 to 102 GtC. These calculations also assume these lands are used for forest product production. This implies that lands that might otherwise be used for forestry would remain undisturbed—that is, these figures also assume some level of avoided deforestation.

The optimal mix of reforestation purely for carbon sequestration and changes in forestry practices in the context of expanding populations and agricultural demands is likely to be determined by a complex set of technical, ecological, economic and policy choices. In addition, many of the reforestation calculations in the literature assume that reforestation activities will be conducted using the most advantageous tree species from a carbon sequestration perspective. At least in some areas, however, one would expect that natural forest regeneration may be preferred for esthetic or ecological reasons. Even given these uncertainties, comparisons with the literature suggest that the reforestation estimates presented here appear to be lower bounds to the amount of carbon that can be sequestered by reforestation.

3.3. Pastureland carbon sequestration

Sequestration in pasturelands represents the smallest component of terrestrial sequestration in all scenarios (Figs. 3 and 4). For reference technology a conservative estimate of an additional 0.2 MgC ha^{-1} over 40 yr (or 8 MgC ha^{-1}) was assumed to be applicable to 40% of pastureland for the 550 ppmv stabilization scenarios. This value is on the lower end of the range seen in the literature, but we assume here that the management changes are completely carbon neutral, which is not the case for some of the practices quoted in the literature. The total global carbon sequestration using this assumption is 4.7 GtC, with management changes assumed to be adopted at the same rate as agricultural soil sequestration practices (Fig. 3c).

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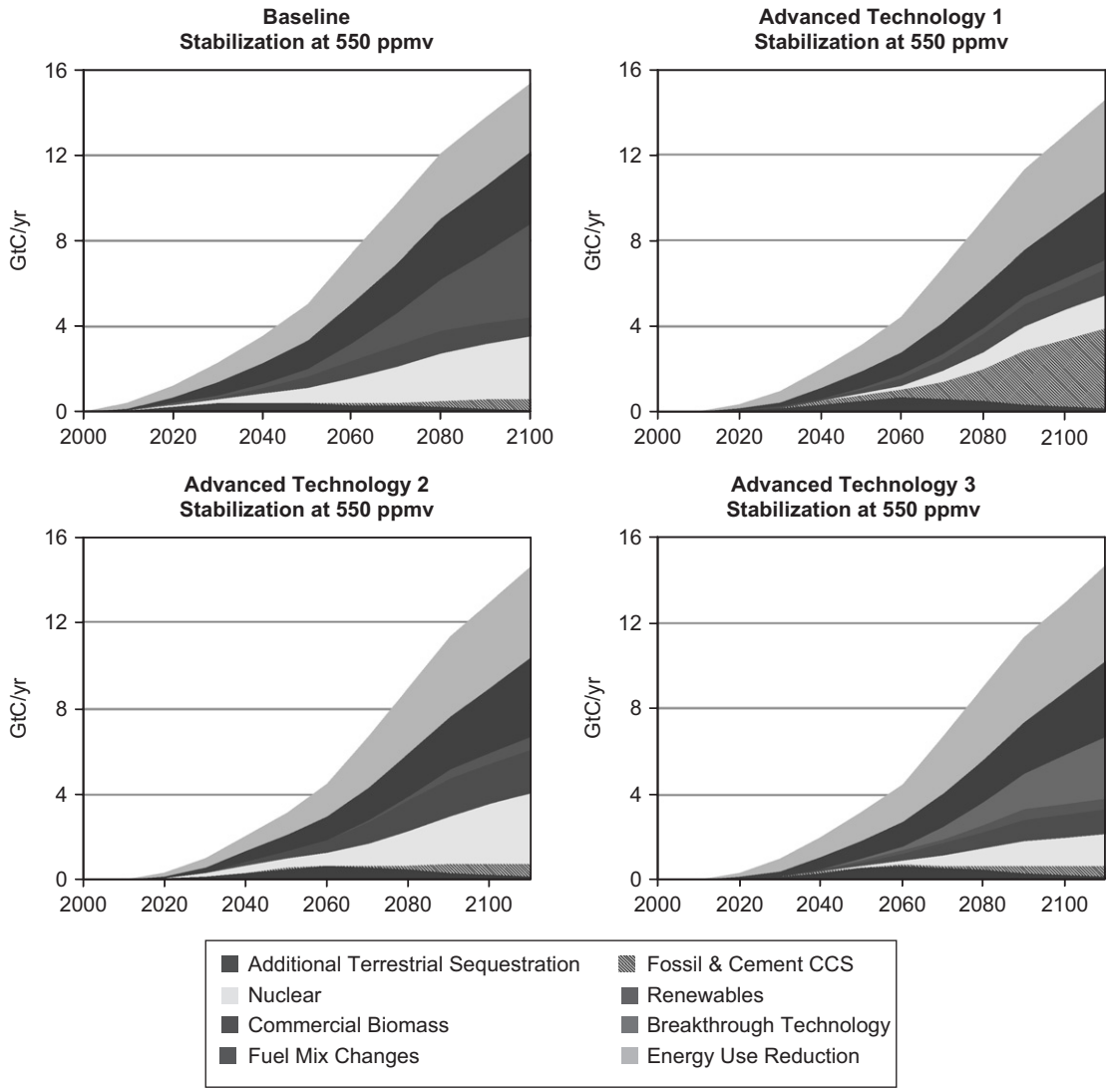

Fig. 5. Contribution of emissions mitigation options in the base and advance technology scenarios with stabilization at 550 ppmv.

In the advanced technology scenarios, the carbon addition was taken to be 0.3 MgC ha^{-1} yr^{-1}, again over 40 yr (12 Mg ha^{-1}), but applied over 60% of pasturelands. This results in 10.6 GtC sequestered over the century for the 550 ppmv stabilization scenarios (Fig. 4c).

3.4. Terrestrial options in a broader context

Developing the terrestrial sequestration options within a broader scenario analysis allowed for comparison of the role of terrestrial sequestration to other options for addressing climate change. Fig. 5 illustrates the role of additional terrestrial carbon sequestration, beyond the amount expected with no climate change policy, in the suite of options considered by the MiniCAM scenario analysis for the reference[3] and advanced technology scenarios. Additional terrestrial sequestration contributes 20% of total carbon emissions mitigation until 2020, when other mitigation options increase rapidly. Terrestrial sequestration then declines as a proportion of total mitigation to about 1% of the total in 2100 as the mitigation necessary to reach the CO_2 stabilization targets increases, carbon prices rise, and other mitigation options expand.

Within this broader, multi-sector context, three observations merit discussion here. First, as shown in Figs. 3 and 4, as a low-cost option, terrestrial sequestration contributes a greater amount of total mitigation under less stringent stabilization targets: 23 Gt of a total 270 Gt for stabilization at 750 ppmv, compared to 41 Gt of a total 962 Gt for stabilization at 450 ppmv. The proportion at 450 ppmv stabilization is smaller, as terrestrial sequestration reaches a practical maximum due to constraints on available land and under competition from other mitigation options.

[3]There is no single way to attribute emissions reductions among energy supply technologies and end use reduction. The split here should be interpreted only as indicative of the relative roles of these different energy sector options for reducing emissions.

Table 3
Percentage of total mitigation contributed to each technology and policy scenario by terrestrial sequestration options

Technology scenario	Policy scenario (ppmv)	2020	2040	2060	2080	2100
Reference	450	10.0	6.2	3.1	1.6	0.6
	550	20.6	13.2	5.2	2.0	0.8
	650	15.5	17.9	8.5	3.4	1.4
	750	16.9	23.4	13.8	5.6	2.1
Advanced	450	15.0	9.0	4.3	2.1	0.8
	550	13.3	17.2	9.1	3.2	1.1
	650	13.3	11.6	11.7	6.2	2.6
	750	10.4	6.2	9.3	10.6	5.5

Terrestrial options are cost competitive at relatively lower carbon prices than many options in the energy sector that are ultimately necessary for stabilization. What varies between the scenarios with respect to terrestrial sequestration options is primarily the relative timing of the mitigation and not the total contribution. This means that terrestrial sequestration contributes a greater portion of the solution with less stringent CO_2 stabilization levels as lower incentives delay the introduction of other mitigation options while the scenarios with more stringent CO_2 stabilization targets result in terrestrial sequestration providing a smaller portion of total mitigation as other technologies become cost competitive very early in the simulation period (Table 3).

Second, although terrestrial sequestration may be an early option for climate mitigation, the full benefits of terrestrial options are not realized immediately. In no scenario does the mitigation from terrestrial sequestration peak before 2040. The contribution from terrestrial options extends throughout the century both because the physical processes require time for taking up carbon and because, in the case of soil options, increasing carbon prices over the century lead to increasing land area for which soil carbon sequestration is economical.

Finally, the scenarios illustrate that carbon mitigation is a multi-technology, multi-sector challenge for which there is no single solution. In all of the scenarios shown in Fig. 5, a multitude of options must contribute to emissions mitigation. Terrestrial sequestration is one of these options. Every option for reducing emissions, including terrestrial options, lowers the emissions reductions required from other sources, and therefore lower the cost of stabilization; but no technology provides the solution alone.

4. Conclusions

These scenarios for terrestrial carbon sequestration represent a global, consistent estimate of the potential for terrestrial carbon sequestration including agricultural soils, reforestation, and pastureland enhancements, consistent with future land-use patterns generated by the MiniCAM integrated assessment model. When combined with mitigation from the energy system, a comprehensive picture of potential future climate mitigation pathways is obtained. In early time periods, additional efforts to enhance terrestrial sequestration can contribute up to 20% of the greenhouse gas mitigation necessary to achieve stabilization. This contribution declines over time as other mitigation technologies mature, emphasizing the role of terrestrial sequestration as an early mitigation option.

In line with estimates in the literature, reforestation has the largest potential, followed by agricultural soils, and then pastureland activities. Significant uncertainties exist in these estimates. For agricultural sequestration important assumptions include the fraction of crops within any given region for which soil sequestration practices can be applied and the longevity of no-till practices. For example, can no-till practices be continued indefinitely or will carbon sequestration be periodically interrupted by tillage? Improved information on current soil conditions and management practices will be necessary to improve estimates of agricultural sequestration potential.

Forest carbon sequestration estimates in the literature vary widely. Much of the variation is associated with different assumptions about the amount and types of land on which reforestation activities could be applied. The nature of the reforestation is also important. There can be significant differences in terms of economic, carbon, esthetic, and ecological benefits between re-growth or regeneration of native forest and a high productivity forest plantation. As intended, the estimates here appear to be a conservative lower bound to forestry sequestration potential.

Many of the options for pasturelands described in the literature involve restoration of degraded lands. Improved information and analysis of both the current state of these lands and their restoration potential are needed. The net greenhouse gas emissions implications of these options need to be determined. We judge that the potential of pastureland options are particularly uncertain.

This analysis has delineated several major issues that must be addressed in the context of integrated assessment. A major uncertainty in evaluations of all terrestrial carbon sequestration is the future allocation of land between competing uses, where large shifts in land use or management could cause shifts in terrestrial carbon stocks greater in magnitude than any considered here. One example is the recent rush to increase biomass energy crop production, an effort which has the potential to alter agriculture, pasture and forestry lands in unforeseen ways. Changes in land management for carbon sequestration also may result in climate feedbacks such as changes in surface albedo (Schaeffer et al., 2006). In addition, limited grounding exists for projections of technological change in land management; however, this analysis shows that even small changes in such aspects as improved crop or forest varieties can make a significant difference in carbon sequestration

potential. The methods established in this paper provide a foundation which will be improved on and more fully integrated into future MiniCAM scenario analyses.

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