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FEATURE

Soil carbon sequestration potential of US croplands and grasslands: Implementing the 4 per Thousand Initiative

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SOIL CARBON SEQUESTRATION

Scientific interest in managing soil organic carbon (SOC) stocks in the United States dates back more than a century because of its importance to soil fertility (Allison 1973), and the importance of the soil-climate nexus was advanced early on by Jenny through his iconic book *Factors of Soil Formation* (Jenny 1941, 1980). However, intensive research on SOC and climate change mitigation really started during the 1990s (Barnwell et al. 1992; Lal et al. 1998c; Paustian et al. 1997). Since then, rates of SOC sequestration through adoption of best management practices have been assessed for diverse land uses and eco-regions throughout the country, including for a wide variety of management practices on cropland (Paustian et al. 1997; Lal et al. 2004; Johnson et al. 2005; Franzluebbers 2005; Ogle et al. 2005; Causarano et al. 2006; Balkcom et al. 2013; Lal et al. 1998c; Martens et al. 2005), such as the inclusion of cover crops (Causarano et al. 2006; Olson 2013; Lal 2015a, 2015b, 2015c; Poeplau and Don 2015; Sainju et al. 2006, 2008); for conversions to perennial grass biofuel plantations (Liebig et al. 2008; Follett et al. 2012); and for improved management on grazing lands (Conant et al. 2001; Schuman et al. 2002; Franzluebbers and Studemann 2009).

The first comprehensive assessments of potential soil carbon (C) sequestration on managed lands for the United States were led by researchers from USDA's Natural Resources Conservation Service (NRCS) and Agricultural Research Service (ARS) and the Carbon Management and Sequestration Center of The Ohio State University (Lal et al. 1995a, 1995b, 1998a, 1998b, 2000a, 2000b, 2001, 2003). These syntheses focused on the potential of US soils to sequester SOC with adoption of best management practices under different land uses (see table 1). Subsequent, more detailed assessments of the technical potential for SOC sequestration at global (IPCC 2000; Smith et al. 2008; Paustian et al. 2016) and US (Sperow et al. 2003; Sperow 2016) scales generally support these earlier estimates of a significant soil C sink potential, on the order of hundreds of teragrams (1 Tg equals 1 million metric tonnes) per year in the United States and roughly an order of magnitude higher globally.

However, there are major economic and policy challenges that must be addressed to harness the potential of soils to mitigate climate change (Lal et al. 2003; Alexander et al. 2015; Paustian et al. 2016; Lal 2016a). Recently, an initiative to encourage national and international programs aimed at promoting soil C sequestration arose at the Paris Climate Summit in December of 2015 with the launch of the 4 per Thousand Initiative (4PT) at global scale (Le Foll 2015).

THE 4 PER THOUSAND INITIATIVE

At the 21st meeting of the Conference of the Parties (COP21) in Paris, the French Minister of Agriculture officially launched the 4PT declaration, "Soils for Food Security and Climate." With the 68th United Nations (UN) General Assembly declaring 2015 as the International Year of Soils, the French Minister of Agriculture, Stephane Le Foll, used the UN declaration and the COP21 negotiations to highlight the climate change mitigation potential of healthy soils (Le Foll 2015). Historic agricultural management has depleted global SOC stocks by as much as 66 ± 12 Pg (petagram [72.8 ± 13.2 billon US tn]) (Lal 1999); taking aggressive steps to move C out of the atmosphere and into healthy soils will help the agricultural sector feed a growing population, buffer against climate change impacts, and contribute to greenhouse gas (GHG) mitigation (Smith 2012). Enhancing SOC stocks will improve infiltration and soil water holding capacity as precipitation events become more intense and regions like California are subject to intense droughts. The French 4PT declaration strives to address global climate change through the aspirational goal of enhancing the C stock on a large portion of the world's managed soils by an average annual increase of 0.4%, hence the "4 per Thousand" moniker. In this analysis, the goals of the 4PT declaration are assessed in the US context, looking for the best opportunities or "bright spots" that could be managed to implement the 4PT program.

SUPPORTIVE MODIFICATIONS TO THE 4 PER THOUSAND DECLARATION

The 4PT expresses an aspirational goal (Lal 2016a, 2016b). With slight modi-

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Table 1

Potential of US soils to sequester carbon (C) and mitigate climate change.

Ecosystem	Land area* (Mha^{-1})	Rate ($Mg\ C\ ha^{-1}\ y^{-1}$)	Total potential ($Tg\ C\ y^{-1}$)	Reference
Cropland	156.9	0.3 to 0.5	45 to 98	Lal et al. (1998c)
Grazing land	336.0	0.04 to 0.21	13 to 70	Follett et al. (2001)
Forest land	236.1	0.11 to 0.43	25 to 102	Kimble et al. (2002)
Land conversion	16.8	0.125 to 0.46	21 to 77	Lal et al. (2003)
Soil restoration	498.4	0.05 to 0.12	25 to 60	Lal et al. (2003)
Other land use	166.0	0.09 to 0.15	15 to 25	Lal et al. (2003)
Total			144 to 432 (288)	Lal et al. (2003)

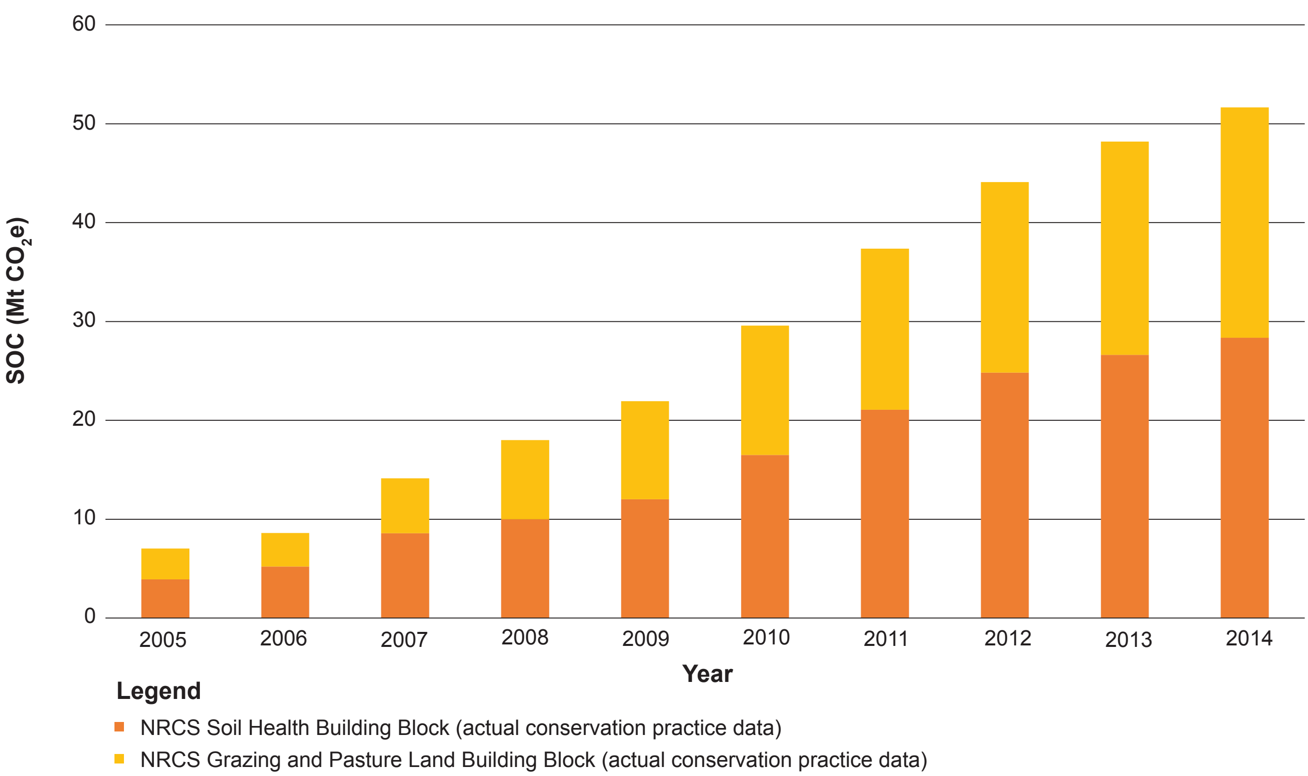
*Land area under different uses cannot be added because of the overlap with total area where "soil restoration" practices could be implemented.

fications, the 4PT declaration could be implemented to quickly produce tangible results in the United States, potentially gaining additional traction throughout the world. For the 4PT declaration to be more palatable to countries with significant soil health initiative experience, like the United States, the following revisions should be adopted into the declaration:

1. Recognize existing soil health activities. The 4PT declaration should adequately recognize existing soil health activities in the United States and elsewhere. Through the leadership of USDA's NRCS and ARS, the United States has already invested in a robust soil health initiative. Since 2005 (fiscal year 2005 to 2014) the NRCS estimates that soil health conservation practices on croplands and grasslands have resulted in a cumulative C sequestration of more than 280 Tg (309 million tn) carbon dioxide equivalent (CO_2e) in the US Secretary of Agriculture's two main SOC Building Blocks for Climate Smart Agriculture and Forestry, (a) Soil Health and (b) Grazing and Pasture Lands. These two USDA Building Blocks align closely with the 4PT declaration (see figure 1).
2. Integrate 4PT policies with United Nations Framework Convention on Climate Change (UNFCCC) reporting. All 196 parties that have signed the 1992 UNFCCC have committed to submitting a National Greenhouse Gas Inventory of Emissions and Sinks. The 4PT declaration seems to have overlooked the opportunity to integrate with the UNFCCC submissions. The United States and other countries, including France, would want to maintain consistency with national GHG reporting criteria, a critical point to consider in the 4PT declaration. Countries like the United States would want to commit to evaluating soil C benefits at the same soil depth as their national inventory. To evaluate national C stocks and stock changes annually, and quantify uncertainty, the United States relies on a complex Tier 3 model-based statistical approach (Ogle et al. 2010) using the DayCent model (Parton et al. 1998; Del Grosso et al. 2000, 2010). However, the United States currently reports national C stocks and annual stock changes (emissions) for the top 20 cm (0 to 8 in) soil layer, while many other countries use Intergovernmental Panel on Climate Change (IPCC) Tier 1 and Tier 2 methods that consider a soil depth of 30 cm (12 in) horizon. The 4PT declaration has introduced yet another depth, 0 to 40 cm (0 to 16.1 in). The 4PT declaration should allow for flexibility on the part of member countries to design policy and monitoring systems in accordance with their national GHG inventory standards and not focus specifically on 0 to 40 cm (0 to 16.1 in).
3. Establish 4PT country-specific targets calculated solely on increasing SOC

Figure 1

USDA Natural Resources Conservation Service (NRCS) progress tracking of soil organic carbon (SOC) enhancements on croplands and grasslands.



stocks, while encouraging countries to achieve targets with a combination of investments in SOC and perennial biomass. The 4PT declaration has been successful at highlighting the need to invest in restoration of soils, increase SOC stocks globally, and protect C-rich soils and biodiversity. A literal interpretation of the target would seem to be appropriate for all countries on soils that can be managed for enhanced C stocks. However, once the target is established for SOC enhancement potential, countries should be encouraged to utilize soil C enhancements as well as long-durational woody conservation plantings, which increase SOC as well as woody biomass C, to help achieve the targets. Conservation practices like cover crops, reduced and no-till adoption, and residue management as well as long-term windbreaks, wooded riparian buffers, and shelterbelts should all be recognized for their atmospheric and soil health benefits. Granted, the 4PT declaration is focused on enhancing global SOC stocks; however, country-specific solutions should allow for both SOC sequestration and C storage in complementary woody biomass installations.

4. Prioritize degraded lands, croplands, grasslands, and agroforestry. The current 4PT declaration considers all lands and associated C stocks—croplands, grasslands, degraded lands, and forest lands. It is difficult to envision soil C sequestration practices that can be practically implemented on many forested lands. Rather than complicate the implementation of 4PT, the authors of the 4PT declaration should consider removing forest soils from the aspirational goals. In the United States, as in France, many forest soils are nationally held in mountainous regions where management of the soils is impractical. In order to transition from aspirational to attainable, the 4PT declaration should focus on degraded lands, croplands, grasslands, and agroforestry lands (windbreaks and other nonforest tree installations).
5. Restore degraded lands. Restoration of mined lands, landslide treatments, and riparian restorations, provide another opportunity to enhance SOC stocks and achieve a modified 4PT goal. The C restoration potential of these degraded lands ranges from 0.3 to 1.3 Mg C ha^{-1} y^{-1} (0.1 to 0.6 tn C ac^{-1} yr^{-1}), higher than many croplands and grasslands conservation practices. The land area is relatively small for degraded lands, but there is significant C sequestration potential on these lands (Lal et al. 1998c, 2003).
6. Commit to tracking progress, global investments in science, and international capacity building. It will require decades to expand global soil C stocks. Similar to the programs implemented in the United States since 1930s through NRCS and ARS, signatory countries will need to develop a comprehensive understanding of C beneficial conservation practices and how the practices impact C stocks based on soil mapping, systematic sampling of soils, and modeling and synthesis techniques. Improving and expanding existing national soil monitoring networks (or where lacking, establishing new monitoring systems) that combine periodic (e.g., every 5 to 10 years) in-field measurement of soils and annual tracking of field management practices (van Wesermael et al. 2011; Spencer et al. 2011) will be essential to track progress and adjust policies over time. Such systems will also greatly improve country-specific GHG inventory reporting.

EVALUATING A REVISED 4 PER THOUSAND SCENARIO FOR SOILS OF THE UNITED STATES

Analysis of 4 per Thousand in United States Context. According to the 2013 US National Inventory of Greenhouse Gas Emissions and Sinks, the top 20 cm (8 in) of cropland and grassland soils in the continental United States contained approximately 16,500 Tg C (18,200 million tn C). These SOC stocks represent the Croplands-Remaining-Croplands, Grasslands-Converted-to-Croplands, Grasslands-Remaining-Grasslands, and Croplands-Converted-to-Grasslands categories within the US National Inventory. Through the imposition of 4PT growth of this top 20 cm (8 in) C stock annually beginning in 2016 and gradually being implemented with a 10-year phase-in period at a yearly increase of 10%, the United States could increase soil C stocks nationally by 250 Tg CO_2e (68 Tg C [75 million tn C]) by 2025, which would thereafter compound at 0.4% annually until SOC stocks plateau at a new equilibrium. With continued investment in bringing areas of agricultural land under a 4PT carbon-building effort, in 2050 this benefit could reach 277 Tg CO_2e y^{-1} (75 Tg C y^{-1} [83 million tn C yr^{-1}]), a level that is approximately half of the entire GHG footprint of the US agricultural sector in 2013.

Taking Stock of Historical Progress of Soil Carbon Building Practices in the United States. In order to track progress toward any soil health or 4PT initiatives, a country must first assess existing C stocks and identify conservation practices that will help the country achieve soil C sequestration. In the United States, the NRCS is the agency with a robust suite of cropland and grassland soil health conservation practices and the capacity to evaluate progress toward achieving soil C sequestration goals. NRCS has developed a national assessment of soil C sequestration practices that would seemingly compliment the 4PT effort. In developing these calculations, NRCS has maintained a base year (2005) consistent with President Obama's COP21 commitment. Since 2005 (inclusive of fiscal year 2005), NRCS soil C sequestering conservation practices on cropland have resulted in building approximately 13 to 43 Tg C (14 to 47 million tn C) when conservatively estimating the direct and long-term conservation legacy effect of the practices.

To attain a decadal goal of aligning with 4PT and increasing C stocks by a minimum of 68 Tg C (75 million tn C), the United States would need to invest in implementing new C-beneficial conservation practices on degraded lands, croplands, and grasslands. Over the past decade (2005 to 2014) NRCS has worked with farmers and ranchers to implement 15 atmospheric-beneficial soil health conservation practices (table 2) on between 4 and 6.9 Mha (10 and 17 million ac) annually (USDA NRCS unpublished).

Table 2

Soil carbon sequestration rates under USDA Natural Resources Conservation Service (NRCS) conservation practices for cropland (adapted from Swan et al. [2015]).

Climate Change Mitigation Building Block	NRCS Conservation Practice Standard Number	NRCS Conservation Practice Standard	Atmospheric/soil benefit (Mg C ha^{-1} y^{-1})
Soil Health	327	Conservation cover (ac) – retiring marginal soils	0.42 to 0.94
	328	Conservation crop rotation (ac)	0.15 to 0.17
	329	Residue and tillage management, no-till (ac)	0.15 to 0.27
	329A	Strip till (ac)	0.07 to 0.17
	329B	Mulch till (ac)	0.07 to 0.18
	330	Contour farming (ac)	0.07 to 0.19
	332	Contour buffer strips (ac)	0.42 to 0.94
	340	Cover crop (ac)	0.15 to 0.22
	345	Residue and tillage management, reduced till (ac)	0.02 to 0.15
	386	Field border (ac)	0.42 to 0.94
	393	Filter strips (ac)	0.42 to 0.95
	412	Grassed waterways (ac)	0.42 to 0.96
	585	Strip-cropping (ac)	0.02 to 0.17
	601	Vegetative barriers (ft)	0.42 to 0.94
	603	Herbaceous wind barriers (ft)	0.42 to 0.95

Over the lifetime of the cropland soil health conservation practices (table 2), it can be expected that NRCS conservation practices sequester approximately 0.07 to 0.96 Mg C ha^{-1} y^{-1} (0.03 to 0.43 tn C ac^{-1} yr^{-1}) for each acre enrolled in soil health conservation practices. With proper management these practices can actively sequester C for 20 years (lifetime approximate benefits range from 1.4 to 19.2 Mg C ha^{-1} (0.6 to 8.6 tn C ac^{-1}). At these C sequestration rates, NRCS and strategic partners would need to recruit approximately 32 to 101 Mha (79 to 250 million ac) out of the total cropland area of 145 Mha (358 million ac) in the United States (in 2013), or a maximum of 70% of all US cropland, to implement atmospheric-beneficial C planning activities. In addition to enrolling land area, each acre would need to be managed for C sequestration, encouraging farmers and ranchers to implement numerous C-enhancing conservation practices to increase the C sequestration potential of each enrolled acre.

Grasslands (Grazing and Pasture Lands Building Block) provide another land-area category for building SOC stocks (table 3). Total US grassland area in 2013 was approximately 175 Mha (432 million ac). Conservatively, NRCS estimates that over the lifetime of conservation practice implementation, 0.02 to 0.44 Mg C ha^{-1} y^{-1} (0.01 to 0.20 tn C ac^{-1} yr^{-1}) can be accrued, on average, on grazing and pasture lands treated with C-focused conservation practices over the coming decade. If 40.5 Mha (100 million ac) of grasslands are treated over the next decade, this could result in a 1 to 18 Tg C y^{-1} (1.1 to 20 million tn C yr^{-1}) benefit, which would reduce the sequestration benefits required from cropland soil health conservation practices. There are a near infinite combination of grassland and cropland conservation practice scenarios that could achieve a 4PT target of 68 Tg C y^{-1} (75 million tn C yr^{-1}), yielding 250 Tg CO_2e y^{-1} (276 million tn CO_2e yr^{-1}) mitigation annually by 2025 with proper focus, strategic partnerships, and diligent investment (figure 2).

Table 3

USDA Natural Resources Conservation Service (NRCS) atmospheric-beneficial grazing and pasture lands and degraded lands conservation practices (adapted from Swan et al. [2015]).

Climate Change Mitigation Building Block	NRCS Conservation Practice Standard Number	NRCS Conservation Practice Standard	Atmospheric/soil benefit (Mg C ha^{-1} y^{-1})
Grazing and Pasture	512	Forage and biomass planting (ac)	0.02 to 0.17
	528	Prescribed grazing	0.17 to 0.44
	550	Range planting	0.22 to 0.35
Degraded Lands Restoration	342	Critical area planting (ac)	0.66 to 1.28
(Not an official	453	Land reclamation: landslide treatment (ac)	0.49 to 1.28
mitigation building block)	543	Land reclamation: abandoned mine lands (ac)	0.67 to 1.28
	544	Land reclamation: currently mined lands (ac)	0.27 to 1.28

Evaluating the Costs and Attainability of Achieving the 4 per Thousand Scenario for Soils of the United States. Over the past decade (2005 to 2014) the NRCS has expended more than US$597 million on implementing the cropland SOC-building (atmospheric/soil-beneficial) conservation practices listed in tables 2 and 3 with cooperation of farmers and ranchers (USDA NRCS unpublished). This investment has resulted in 13 to 43 Tg C (14 to 47 million tn C) sequestration in the soil health conservation practices (USDA NRCS forthcoming). Thus the cost ranges from about US$3.80 to US$12.50 Mg^{-1} (US$3.44 to US$11.34 tn^{-1}) CO_2e. These costs do not include the value of co-benefits. During the same decade, NRCS conservation practices achieved approximately 9 to 31 Tg C (10 to 34 million tn C) sequestration benefits on grasslands at a total cost of US$355 million. Thus the cost for grassland C sequestration ranged from about US$3.10 to US$10.75 Mg^{-1} (US$2.81 to US$9.75 tn^{-1}) of CO_2e.

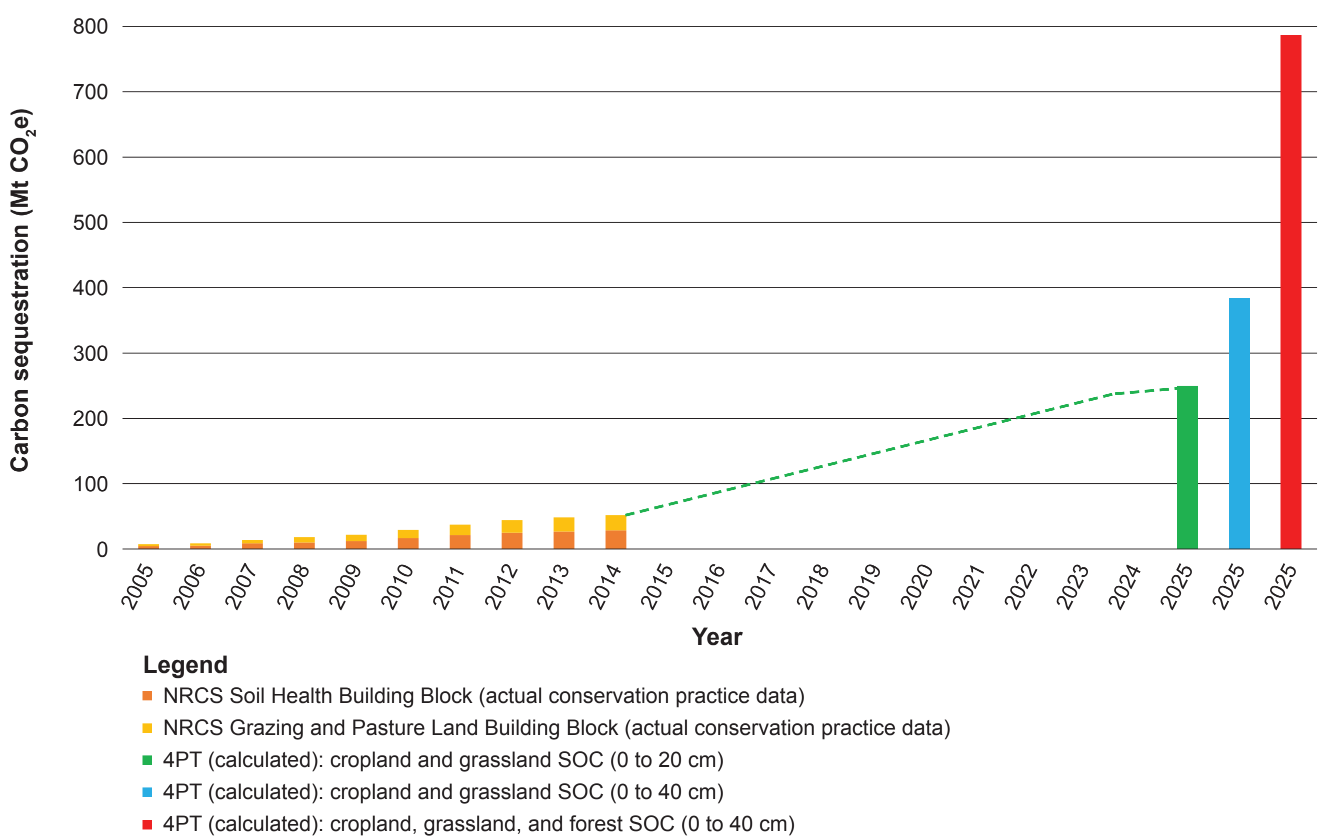
NRCS investment in promoting voluntary soil health conservation practices has delivered a maximum of 14 Tg C (15 million tn C) sequestration annually (in 2014), and thus to achieve a 4PT target of 68 Tg C y^{-1} (75 million tn C yr^{-1}) will require significant additional partnerships and additional resources. In order to achieve annual C benefits of 68 Tg C y^{-1} (75 million tn C yr^{-1}), the national investment in healthy soils and soil C building practices may need to grow exponentially. There would also need to be a coordinated effort to expand the promotion of soil health and expand the climate change mitigation potential. Costs in this analysis only represent farm bill financial assistance distributed to agricultural producers and do not include the farmer's and rancher's contribution, nor do these costs include the cost of government staff time for conservation planning and technical assistance. Granted, achieving an additional 68 Tg of C (75 million tn C) sequestration annually on cropland and grassland soils by 2025 could cost several billion dollars (US$3 to US$5 billion), but the costs of enhancing C stocks in healthy soils can be viewed as an investment in the future (Lal et al. 2003).

The majority of US cropland and grassland soils have the capacity to increase C stocks consistent with the 4PT initiative; it would be important to focus on top soil (0 to 20 cm [0 to 8 in]) C stocks and prioritize degraded lands, cropland, and grassland. This analysis does not consider the potential of break-through genetic technologies like deep rooting crop phenotypes or application of off-farm C sources like compost and biochar.

To attain the 4PT goal, the United States would need to commit to a long-

Figure 2

USDA Natural Resources Conservation Service (NRCS) atmospheric-beneficial conservation practices and bridging to 4 per Thousand on croplands and grasslands (0 to 20 cm).



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term soil health strategy where, on average, 4.1 Mha (10 million ac) of croplands and 8.1 Mha (20 million ac) of grasslands are enrolled annually in C-beneficial conservation practices for the next decade. Every field would require an individualized conservation plan focused on enhancing the C sequestration potential of the soils underlying that field. Farming, ranching, and management practices would need to be modified to maximize the soil health and C sequestration benefits of individual fields while respecting the food and fiber production requirements of agricultural producers. Through this ambitious, yet attainable approach, the soils of the United States can begin playing a larger role in reducing atmospheric concentrations of CO_2 while also building a more resilient landscape for the future. The green dashed line in figure 2 is a challenging pathway to accomplishing 4PT in cropland and grassland soils of the United States. Although ambitious, this pathway seems low-risk and high-return.

CONCLUSIONS

Reducing the severity of anthropogenic climate change is one of the great challenges facing humanity. Land use, currently accounting for about 25% of global GHG emissions, must be part of an effective climate change mitigation strategy. Furthermore, it may not be possible to achieve large enough emissions reductions in the energy, transport, and industrial sectors alone to stabilize GHG concentrations at a level commensurate with a less than 2°C (3.6°F) global average temperature increase, without the help of a substantial CO_2 sink from the land use sector (IPCC 2014).

The 4PT proposal sets a laudable goal of actively engaging agriculture as part of the climate change solution and is the first global-level initiative of its kind. However, to increase the probability of success, the 4PT initiative should incorporate sufficient flexibility to meet the needs of individual countries and to mesh with ongoing national efforts to achieve goals of promoting soil C sequestration.

Thus, USDA NRCS's soil health initiative must be accounted for and considered in target-setting under the 4PT initiative. Similarly, ongoing soil C research in USDA's soil research agencies and US universities can contribute to achieving the 4PT vision. The development of inventory and monitoring technologies for soil C and other emissions is among the strengths of these US institutions.

Additionally, the 4PT initiative needs credible and transparent means for monitoring, reporting, and verifying GHG reduction benefits that are compatible with national GHG inventory procedures. Rather than specifying a fixed 0 to 40 cm (0 to 16 in) basis for country-specific 4PT goals, soil C stock accounting must be harmonized with country-level GHG inventory standards. Individual countries must have the flexibility to prioritize the land area and soils where adoption of soil C sequestering practices can have the greatest benefit and be most cost-effective.

Setting both interim (e.g., 2025) and long-term (e.g., 2050) goals and establishing performance tracking (e.g., every five years) to evaluate and adjust ongoing programs will help ensure that 4PT goals are attained. Finally, rebuilding the organic matter capital of managed soils represents a long-term investment, and 4PT countries will need to commit to a long-term implementation plan that includes quantification and inventory improvements to ensure that soil health, soil information systems, and C sequestration benefits are maximized.

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