Soil Carbon 4 per mille

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ABSTRACT

The '4 per mille Soils for Food Security and Climate' was launched at the COP21 with an aspiration to increase global soil organic matter stocks by 4 per 1000 (or 0.4 %) per year as a compensation for the global emissions of greenhouse gases by anthropogenic sources. This paper surveyed the soil organic carbon (SOC) stock estimates and sequestration potentials from 20 regions in the world (New Zealand, Chile, South Africa, Australia, Tanzania, Indonesia, Kenya, Nigeria, India, China Taiwan, South Korea, China Mainland, United States of America, France, Canada, Belgium, England & Wales, Ireland, Scotland, and Russia). We asked whether the 4 per mille initiative is feasible for the region. The outcomes highlight region specific efforts and scopes for soil carbon sequestration. Reported soil C sequestration rates globally show that under best management practices, 4 per mille or even higher sequestration rates can be accomplished. High C sequestration rates (up to 10 per mille) can be achieved for soils with low initial SOC stock (topsoil less than 30 t C ha^{-1}), and at the first twenty years after implementation of best management practices. In addition, areas which have reached equilibrium will not be able to further increase their sequestration. We found that most studies on SOC sequestration only consider topsoil (up to 0.3 m depth), as it is considered to be most affected by management techniques. The 4 per mille number was based on a blanket calculation of the whole global soil profile C stock, however the potential to increase SOC is mostly on managed agricultural lands. If we consider 4 per mille in the top 1m of global agricultural soils, SOC sequestration is between 2-3 Gt C $year^{-1}$, which effectively offset 20–35% of global anthropogenic greenhouse gas emissions. As a strategy for climate change mitigation, soil carbon sequestration buys time over the next ten to twenty years while other effective sequestration and low carbon technologies become viable. The challenge for cropping

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farmers is to find disruptive technologies that will further improve soil condition and deliver increased soil carbon. Progress in 4 per mille requires collaboration and communication between scientists, farmers, policy makers, and marketeers.

Contents

1. Introduction

The COP21 or 21st Conference of the Parties to the United Nations Framework Convention on Climate Change in Paris (November 30 to December 11, 2015) produced the Paris Climate Agreement. This is a global agreement on the reduction of climate change, limiting global warming to less than 2 Celsius degrees (C°) compared to pre-industrial levels and to pursue efforts to limit the increase to 1.5 C°. In order to keep warming below 2 C°, we need to limit our annual greenhouse gas emission with an estimate of 9.8 Gt (9.8×10^{15} g) C at a 64% probability (Meinshausen et al., 2009). The Paris Agreement has been entered into force on 4 November 2016. As of November 2016, there have been 192 signatories and 114 of those parties have ratified the Agreement.

At COP21, the French Minister of Agriculture Stéphane Le Foll set an ambitious international research program, the '4 per mille Soils for Food Security and Climate' of the Lima-Paris Action Agenda. The 4 per mille or 4 per 1000 aspires to increase global soil organic matter stocks by 0.4 percent per year as a compensation for the global emissions of greenhouse gases by anthropogenic sources. It was launched during COP21 in December 2015 and supported by almost 150 signatories (countries, regions, international agencies, private sectors and NGOs). Stakeholders commit in a voluntary action plan to implement farming practices that maintain or enhance soil carbon stocks in agricultural soils and to preserve carbon-rich soils (Chambers et al., 2016; Lal, 2016).

Soil organic carbon (SOC) sequestration has been considered as a possible solution to mitigate climate change, to take atmospheric CO_2 and convert it into soil carbon which is long-lived. As soil stores two to three times more carbon than the atmosphere, a relatively small increase in the stocks could exert a significant role in mitigating greenhouse gases emissions. The annual greenhouse gas emissions from fossil carbon are estimated at 8.9 giga tonnes C (8.9×10^{15} g), and a global estimate of soil C stock to 2 m of soil depth of 2400 giga tonnes (2400×10^{15} g) (Batjes, 1996). Taking the ratio of global anthropogenic C emissions and the total SOC stock (8.9/2400), results in the value of 0.4% or 4‰ (4 per mille) (Fig. 1). Increasing SOC has been proposed to mitigate climate change with an additional benefit of improving soil structure and conditions (Lal, 2016).

If we take the land area of the world as 149 million km^2, it would be estimated that on average there are 161 tonnes of SOC per hectare. So 4 per mille of this equates to an average sequestration rate to offset emissions at 0.6 tonnes of C per hectare per year. This 4 per mille blanket value cannot be applied everywhere as soil varies widely in terms of C storage, which includes desert, peatlands, mountains, etc. Soil types, aboveground vegetation, climate, and how quickly the soil biota uses the carbon collectively impact C storage (Fig. 2). Nevertheless, studies across the globe have measured SOC sequestration rates and they suggest that an annual rate of 0.2 to 0.5 tonnes C per hectare is possible (Table 1), after the adoption of best management practices such as reduced tillage in combination with legume cover crops. There are reports on SOC increase in some parts of the world due to improved management (e.g. Chen et al., 2015), however a study on the global C stock in the world showed that some cropland areas have contents that are below critical limits (Stockmann et al., 2015). The best strategy is to restore the SOC content in these degraded areas, as it offsets greenhouse gas emissions and provides benefits of enhanced soil conditions.

This paper brings together a survey of SOC experiences from 20 regions of the world. We reviewed the SOC stock estimates of each region and asked whether the 4 per mille initiative is feasible. As a convention in this paper, C unit mass is expressed in tonne (t, 10^6 g), and the unit area in hectare (ha, 10^4 m^2). C stock is expressed in Mt (equivalent to Tg or 10^{12} g) or Gt (equivalent to billion tonne, 10^3 Mt, Pg or 10^{15} g), sequestration rate is expressed in tonne C per hectare per year (1 t C ha^{-1} year^{-1} is equivalent to 0.1 kg C m^{-2} year^{-1}) to a specified depth.

2. Regional case studies

The following case studies are arranged from south to north in the order of the region's centroid latitude. The maps of soil carbon stocks (0–0.3 m) are in t C ha^{-1}, projected in the Mercator projection system (Figs. 2-12).

2.1. New Zealand

Carolyn Hedley

The estimated mean SOC stocks in New Zealand are 98.7 t C ha^{-1} to a depth of 0.3 m (Fig. 3). To meet the 0.4% initiative, New Zealand will require a SOC sequestration rate of approximately 0.4 t C ha^{-1} year^{-1}.

The New Zealand Ministry for the Environment (MfE) established the Soil Carbon Monitoring System (Soil CMS) for annual reporting on the land use, land-use change, and forestry (LULUCF) sector in the national greenhouse gas inventory, submitted to the United Nations Framework Convention on Climate Change (UNFCCC). This system provides evidence for larger SOC stocks in long-term pastoral soils compared with established forest land (New Zealand Ministry for the Environment, 2015). Therefore, land use change from forest to pasture sequesters soil carbon over a period of decades. However, there are limited opportunities to convert more forest land to pasture, and this conversion would need to account for the loss of biomass C, making this option less favourable.

Current challenges are to maintain or enhance already high levels of SOC stocks in New Zealand's productive grazed pastoral soils, as well as find other practical ways to sequester C into soil. The peaty soils associated with our vegetated wetland areas have the largest SOC stock at an estimated 136.06 t C ha^{-1}. However, when drained for productive use they rapidly lose SOC through oxidation of the organic matter, estimated at a rate of 2.94 t C ha^{-1} year^{-1} (Campbell et al., 2015). Thus establishing or restoring wetlands can contribute to SOC accumulation. These

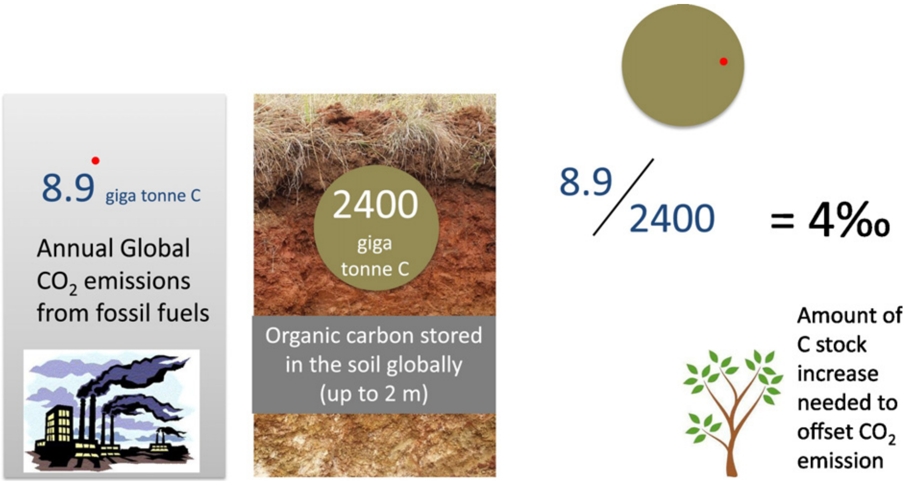


Fig. 1. The 4 per 1000 soil carbon sequestration initiative (adapted from Ademe, 2015).

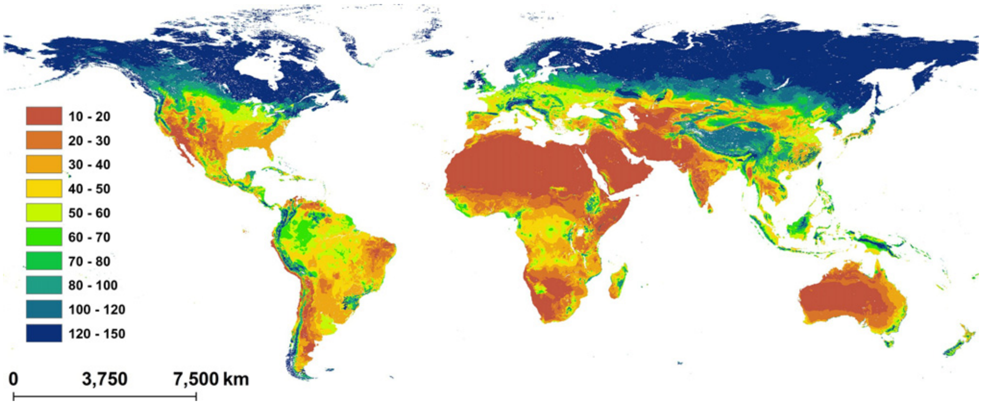


Fig. 2. Soil C stocks of the world's topsoil (0–0.3 m) in tonne C per hectare. The map was generated based on global datasets of C stock from the study of Stockmann et al. (2015).

wetlands could be established in areas otherwise unsuitable for productive agriculture, e.g. high country and floodable areas.

Work undertaken to assess erosion impacts on SOC for LULUCF reporting found that landslides cause a significant net decline in soil C stocks, with eroded sites only recovering to 70–80% of original levels. However, rates of soil carbon accumulation in recent erosion scars have been measured at 1–3 t C ha^{-1} $year^{-1}$ for the first 10 years, and 0.4–1.1 t C ha^{-1} $year^{-1}$ over a 70-year period (Lambert et al., 1984; De Rose, 2013; Basher et al., 2011). These studies provide useful data on potential rates of SOC sequestration when degraded land rehabilitates to pastoral land use.

SOC stock-change trajectories in long-term managed grasslands have been investigated by resampling some flat pastoral sites previously sampled about 30 years earlier, and the study reported small SOC stock losses at these selected sites ($n = 125$; Table 1). However, a study by Parfitt et al. (2014), using a different subset of flat pastoral sites as part of a regional soil quality monitoring program, reported increasing SOC, with change rates between 0.32 ± 0.19 t C ha^{-1} $year^{-1}$ and 0.57 ± 0.31 t C ha^{-1} $year^{-1}$, for dairy and dry stock flat land respectively ($n = 139$). Both researchers observed increasing SOC stock at a small number of stable positions in the hill country ($n = 19$–23); with possible reasons given being: reduced overgrazing, and/or a gradual long-term recovery of soil organic matter following erosion when forests were originally cleared.

Parfitt et al. (2014) linked changes in SOC to soil pH and P fertility, finding the sites they resampled that had decreased in pH had significant gains in C, whereas sites that had increased in pH had no significant gains in C, with possible reasons being that high pH (due to liming) and increased P fertility indicate more intensive management, thereby reducing SOC. Alternatively, there could be enhanced relocation of dissolved organic carbon to greater depths in soils of lower pH.

Percival et al. (2000) showed a positive relationship of SOC content to pyrophosphate-extractable Al, Fe oxide, allophane and clay content in New Zealand soils.

Current research topics (http://www.nzagrc.org.nz/soil-carbon.html) on ways to sequester C include:

- assessing the gap between current and potential levels of carbon storage in New Zealand soils
- assessing the effect of the more frequent renovation of dairy pastures, and mixed sward compositions.
- assessing the effect of biochar additions to soils, including the economics of incentives for land managers to apply biochar to land.

In conclusion, SOC in New Zealand soils is naturally high. Opportunities to sequester SOC include the creation or re-establishment of wetlands, and land use change (taking into account any impacts on biomass C). Current knowledge suggests that ways to sequester SOC will include targeting specific soil classes (e.g. allophanic soils), and/or specific landscape positions (e.g. wetlands) and using appropriate management strategies.

Efforts by landowners to sequester carbon into soil will need to be supported by improved ways of monitoring change, and New Zealand will need to develop a purpose-built sampling and monitoring protocol to address this challenge.

2.2. Chile

José Padarian

The top 0.3 m SOC stock estimate for Chile is 5.52 Gt and 9.8 Gt for the top 1 m (Fig. 4, Padarian et al., 2016). A 4 per mille increase per annum would translate to the capture of 39.2 Mt of carbon across the country, which is enough to offset its CO_2 emissions (19.11 Mt C, excluding Land Use Change and Forestry, LUCF), or offset 21.8% of the total GHG emissions (42.3 Mt of CO_2 equivalent, excluding LUCF). However if we only look at the agricultural area which only occupies 4.6% of the land area, the C stock for the top 1 m is 0.25 Gt.

Chile presents a clear north-south gradient of precipitation and temperature, and consequently SOC distribution, which divides the territory into areas prone to different management and SOC capture potentials. The northernmost part of the territory is dominated by arid and hyper-arid conditions (Atacama dessert), with virtually no vegetation and a capture potential very close to zero, except for small amounts from atmospheric deposition (Ewing et al., 2008). A gradient of C stock along a north–south transect of grassland was observed, where soil C stock is a function of the interaction between climatic and geochemical factors (Doetterl et al., 2015). In the southernmost area, it is possible to find a large area of peatlands of about 4.5 Mha (Yu et al., 2010). The composition of the vegetation communities of this landtype varies across the landscape but, on average, it accumulates around 0.16 t C ha^{-1} $year^{-1}$ (McCulloch and Davies, 2001), which translates to 6.3 Mt per annum for the whole area. The current legislation fails to protect this fragile ecosystem, and many areas are being drained to establish forest plantations or being extracted for peat.

Due to geographical and economic factors, the area of cultivated lands is limited to about 2.1 Mha, where most are under traditional management. In this area, it is possible to extend the use of management practices like zero tillage or crop rotation, with a potential increase of 0.5 t C ha^{-1} $year^{-1}$ where water is not limiting (Martínez et al., 2013), leading to 1.05 Mt C sequestered per annum. In Patagonia, a soil C sequestration rate of 0.87, 0.34, and 1.09 t C ha^{-1} $year^{-1}$ was calculated for silvopasture, plantation and prairie system respectively (Dube et al., 2011).

Chile presents several governmental programs to enhance soil conditions, which finance managements that may lead to an increase of SOC. For example, reforestation and implementation of zero tillage. Additionally, Chile also adopted international commitments like the implementation of Nationally Appropriate Mitigation Actions (NAMAs), which include a strong forest component, with plans to afforest about 2.29 million ha. The accumulation rates will depend on the soil type, species, and climatic conditions (Schlatter and Gerding, 2001).

In summary, it is feasible to offset the current CO_2 emissions by increasing SOC in agricultural land by improving management, afforesting degraded areas and conserving delicate land uses like native forest and peatlands. It is important to consider that soils cannot store OC indefinitely and that GHG emissions tend to increase. It is also important to remember that even if there are good intentions creating new legislation and subscribing to international treaties, the implementation plans have to be correctly defined. For instance: a) at the moment, SOC and minimal residence time are not specifically mentioned, or b) a significant part of the offset is to be performed by the forest industry (NAMAs also include a carbon credits market), but without a modification of the current management system (clear-cut), the benefits associated with the NAMAs will be another transfer of funds to the private sector. It is important to remember that the forest industry greatly benefited during a military dictatorship (1973–1990), where state-owned forest lands were sold to private companies at artificially depressed prices. To reinforce this change, a reform was implemented in 1974, which included subsidies for plantation costs and tax exceptions. With the help of consecutive subsidies, tax credits, and the prohibition of union activity (Wilson et al., 2005), the private forest industry assured its position as an important economic activity in Chile, despite the multiple problems associated with it, such as the negative impact on the hydrological cycle (Little et al., 2009), biodiversity loss and deforestation (Echeverría et al., 2006; Nahuelhual et al., 2012), and the decrease of social security, especially in aboriginal communities (OLCA, Observatorio Latinoamericano de Conflictos Ambientales, 2003).

2.3. South Africa

Vincent Chaplot

South Africa occupies 1,214,470 km^2 in the southern tip of Africa, with longitudes from 3.3° to 38.0° E and latitudes from 54.5° to 22.1° S. Altitude above sea level ranges from 0 to nearly 4000 m with South Africa's landscape being dominated by a high Central Plateau, the Drakensberg, surrounded by coastal lowlands. The Savannah Biome, characterized by a grassy ground layer and a distinct upper layer of woody plants covers 30% of South Africa's area. It is well developed over the Lowveld and Kalahari region of South Africa. It is followed by grassland (30%), mostly concentrated in the east of the country on the high central plateau, thicket (predominantly in the river valleys of the eastern and southeastern coastal region) and forest (less than 5%). With a mean annual rainfall of approximately 450 mm, South Africa is regarded as semi-arid. However, there are considerable regional variations, from less than 50 mm in the Richtersveld on the border with Namibia, to more than 3000 mm in the mountains of the southwestern Cape. The soils of South Africa range from black, smectitic clays on intrusive basic rocks to yellow, sandy to clayey kaolinitic soils on the sedimentary Karoo rocks.

Analytical data from 1433 soil profiles from the national land survey demonstrated that the top 1 m holds an estimated 11.42 Gt of SOC, 65% of which (7.03 Gt) is in the top 0.3 m. SOC stocks are the highest (>400 t C ha^{-1}) in the eastern and southern more rainy areas of the country (Fig. 5).

Shifts in rangeland (savannahs and natural and semi-natural grasslands) management may yield the greatest benefits for C sequestration in the country. Indeed, on the one hand, rangelands which cover about 50% of the area and 75% of SOC stocks, suffer from severe land degradation that have resulted from inappropriate management, with SOC stock losses of as much as 90% (Dlamini et al., 2014). On the other hand, improved grassland management involving short duration high density grazing resulted in measurable SOC sequestration in the topsoil (Chaplot et al., 2016). While options for croplands such as no tillage did not result in SOC gains (Mchunu et al., 2011). Depending on the method of calculation, it is estimated that up to 60% of South Africa's rangelands are degraded and assuming losses of 30–50% in the top 0.3 m of the soil, the carbon sequestration potential could be of 1.44 to 2.41 Gt. With a sequestration rate of 3.5%, this would correspond to 0.08–0.11 Gt C $year^{-1}$.

The South African government has been proactive in respect to carbon stocks and associated GHG emissions in natural and semi-natural ecosystems with 39 policies. These mostly aim at limiting the spread of alien invasive plants, controlling vegetation fire and restoring wetland and woodland systems. However, new policies need to target the urgent need for rangeland improvements with specific targeted intervention strategies and associated carbon sequestration and/or conservation benefits.

2.4. Australia

Uta Stockmann, Brendan Malone, Damien Field, Alex. McBratney

The Australian soil carbon stock has been estimated to be 25 Gt in the top 0.3 m (Viscarra Rossel et al., 2014), and of 49 Gt to 1 m depth (Fig. 6). Because of its large landmass, Australia could potentially play an important role in the global 4 per mille SOC sequestration initiative. If we only consider agricultural land at 470 million ha, a 0.4% increase means, on average, a sequestration rate of 0.22 t C ha^{-1} $year^{-1}$. This suggested sequestration rate falls within measured rates of C sequestration after the adoption of best-management practices in Australia, where water is not severely limiting (0.1–0.4 t C ha^{-1} $year^{-1}$, see Table 1).

However, in Australia soil carbon stocks vary greatly across the continent and correspond largely to differences in mean annual temperature, precipitation, soil profile class, and soil moisture content (Fig. 6, Bui et al., 2009). In general, soil carbon stocks are naturally quite small except in the Eastern regions of the country, with C stocks in undisturbed, natural ecosystems ranging between <10 t/ha in arid regions and 250 t/ha in cooler and wetter regions such as coastal swamps and Tasmania (Luo et al., 2010). From a soil C stock map, small soil C values are found in the sandy soils of the Northern Territory and Western Australia (required C sequestration rate <0.1 t C ha^{-1} $year^{-1}$); moderate values (1–2% SOC) in the inland areas (0.1–0.2 t C ha^{-1} $year^{-1}$); large values in the coastal areas (0.3–0.4 t C ha^{-1} $year^{-1}$) and very large soil C values generally under natural vegetation (1 t C ha^{-1} $year^{-1}$).

Studies have shown that soils worldwide have lost almost half of their initial C levels after the introduction of soil management practices (Paustian et al., 2000). For Australia, the largest loss of soil C of up to 0.4 t C ha^{-1} $year^{-1}$ was reported for conventional cultivation practices combined with stubble burning in an annual wheat cropping system (Luo et al., 2010). Best management practices have the capability to reverse this C loss as they generally maintain or increase soil C levels (Table 1). For example, Sanderman et al. (2010) reported that crop rotations — particularly ones that include a leguminous species (Murphy, 2015) — stubble retention and reduced tillage achieved an annual increase of soil C in the Australian environments studied; with sequestration rates of 0.20 C ha^{-1} $year^{-1}$, 0.19 C ha^{-1} $year^{-1}$ and 0.34 t C ha^{-1} $year^{-1}$, respectively.

The rate of soil C build up however also depends on soil type (Hoyle et al., 2013) with largest changes observed for cropping practices in Kandosols (Cambisols, WRB) and Chromosols (Lixisols, WRB), and smallest changes observed in Vertosols (Vertisols, WRB) (Murphy, 2015). In addition, the potential for soil C increase is also dependent on the availability of moisture which controls the decomposition of biomass, with largest changes occurring where the rainfall is between 400 to 600 mm (Luo et al., 2010).

On 25 July 2014, the Australian Government approved the first systems methodology for soil carbon sequestration. Farmers can adopt this methodology, and provided that they are changing some aspect of their grazing practice that will lead to measurable soil carbon increases, can earn regulated carbon credits that can be sold on the market. Cost-

Table 1
Management practices that are reported to sequester soil carbon.

Management practices	Country	Depth observed	Carbon sequestration rates[b] $t\ C\ ha^{-1}\ yr^{-1}$	Average C stock[a] $t\ C\ ha^{-1}$	Period of observation	References
Arable land						
Organic amendment	China	Plough layer, 0–20 cm for dry cropland and 0–15 cm for paddy soil	0.62	24.4	*6 to 25 years, 14.4 years on average	Wang et al. (2010)
Organic amendment	China	Plough layer	0.54	24.4	*3 to 25 years	Jin et al. (2008)
Organic amendment combined with inorganic fertilizer	China	Plough layer, 0–20 cm for dry cropland and 0–15 cm for paddy soil	0.62 0.69 0.89	24.4	*3 to 25 years	Jin et al. (2008); Zhu et al. (2015); Wang et al. (2010)
Compost addition	S. Korea	0–30 cm paddy soils	0.24	40.5	42 years	Lee et al. (2013)
Compost addition with inorganic fertilizer	S. Korea	0–30 cm, paddy soils	0.39	40.5	42 years	Lee et al. (2013)
Compost addition	Taiwan	0–15 cm	0.46–1.00	36	*13–20 years	Wei et al. (2015a); Wei et al. (2015b)
Compost with inorganic fertilizer	Taiwan	0–15 cm	0.40–0.80	37.4	*20 years	Wei et al. (2015a); Wei et al. (2015b)
Farm yard manure (@0.16 Mg C/ha/yr)	Belgium	0–25 cm	0.45 ± 0.14	50	*20 years	Buysse et al. (2013)
Farm yard manure/crop residue	Nigeria	Topsoil	0.10–0.30	33.4	*50 years	FAO (2004)
Inorganic fertilizer with straw return	Indonesia	0–15 cm, paddy soils	0.52 ± 0.16	17.9	40 years	Minasny et al. (2012)
Straw return with Inorganic fertilizer	Indonesia	0–15 cm, paddy soils	0.47	17.9	*3 years	Sugiyanta (2015)
Inorganic fertilizer	S. Korea	0–15 cm, paddy soils	0.32 ± 0.29	27.3	8 years	Minasny et al. (2012)
Straw return	China	Plough layer	0.57–0.60	27.6	*3 to 25 years	Jin et al. (2008); Lu et al. (2009)
Rice-Rice with NPK	India	0–20 cm	0.23	31.3	36 years	Mandal et al. (2008)
Rice-Rice with NPK + compost	India	0–20 cm	0.41	31.3	36 years	Mandal et al. (2008)
Rice-Wheat with NPK	India	0–60 cm	0.66	34.4	19 years	Majumder et al. (2008)
Rice-Wheat with NPK + Farm yard manure (FYM)	India	0–60 cm	0.99	34.4	19 years	Majumder et al. (2008)
Rice-Wheat with NPK + Paddy straw	India	0–60 cm	0.89	34.4	19 years	Majumder et al. (2008)
Rice-Wheat with NPK + Green manuring	India	0–60 cm	0.82	34.4	19 years	Majumder et al. (2008)
Inorganic fertilizer	India	0–15 cm	0.16	13.3	6–32 years	Pathak et al. (2011)
Inorganic fertilizer + FYM	India	0–15 cm	0.33	13.3	6–32 years	Pathak et al. (2011)
Residue incorporation	Nigeria	0–15 cm	0.24	20	*18 years	Raji and Ogunwole (2006)
Stubble retention	Australia	0–15 cm	0.19 ± 0.08	21.2	*	Sanderman et al. (2010)
Stubble retention	Australia	0–10 cm	0.147 ± 0.059	18.3	*4 to 40 y	Lam et al. (2013)
No till	China	Plough layer	0.16–0.51		3 to 25 years	Jin et al. (2008); Lu et al. (2009); Wang et al. (2009)
No till	France	0–30 cm, Wheat-corn rotation	0.2 ± 0.13	51.6	20 years	Arrouays et al. (2002b)
No till	UK	Topsoil	0.31 ± 0.2	80	5–23 years	Powlson et al. (2012)
No till	USA	0–20 or 0–30 cm	0.4 ± 0.61[c]	53±25.2	12–34 years	Johnson et al. (2005)
No till plus cover crops	USA (southeast)	0–20 cm	0.45 ± 0.04	25.5 ± 0.9	11 ± 1 years	Franzluebbers (2010)
Conventional till to no-till	Canada	0–30 cm	0.05–0.16	75	20 years	VandenBygaart et al. (2008)
Reduced use of summer fallow	Canada	0–30 cm	0.30	75	20 years	VandenBygaart et al. (2008)
Reduced tillage	Australia	0–15 cm	0.34 ± 0.06	21.2	*Various, 4 to 42 years	Sanderman et al. (2010)
Reduced tillage	Belgium	0–60 cm	0		20 years	D'Haene et al. (2009)
Conservation tillage	Australia	0–10 cm	0.15 ± 0.028	18.3	4 to 40 years	Lam et al. (2013)
Conservation tillage	France	0–25 cm	0.10	51.6	28 years	Metay et al. (2009)
Crop rotation	Australia	0–15 cm	0.20 ± 0.04	21.2	Various, 4 to 42 years	Sanderman et al. (2010)
Crop rotation	France	0–30 cm	0.16 ± 0.08	51.6	20 years	Arrouays et al. (2002a,b)
Crop rotation with perennial grasses	Russia	Plough layer	0.03–0.08	32.3	*5 years	Savin et al. (2002)
Conversion to ley farming	England	0–23 cm	0.20	80	30 years	Powlson and Johnston (2015)
Conversion of annual cropping to crop + ley rotation	USA	0–30 cm	0.5	78	30 years	Dick et al. (1998)
Grassland						
Cropping to pasture	Australia	0–15 cm	0.30–0.60	27.5	4 to 42 years	Sanderman et al. (2010)
Cropping to pasture	Australia	Pasture rotation, 0–30 cm from 33% to 67% pasture	0.22–0.76	43	10 years	Chan et al. (2011)
Cropping to pasture	Australia	Pasture to improved pasture	0.76	43	10 years	Chan et al. (2011)
Cropping to pasture	Australia	0–30 cm	0.78	31	4.7 years	Badgery et al. (2014)
Cropping to pasture	France	0–30 cm	0.49 ± 0.26	51.6	20 years	Arrouays et al. (2002a,b)
Cropping to pasture	England	0–23 cm	0.51	80	35 years	Goulding and Poulton (2005)
Pasture	Australia	0–10 cm	0.132 ± 0.054	18.3	4 to 40 years	Lam et al. (2013)
Pasture	Australia	0–30 cm, perennial and annual pasture	0.759 ± 0.049	35	7 years	Chan et al. (2011)

Table 1 (*continued*)

Management practices	Country	Depth observed	Carbon sequestration rates[b] t C ha^{-1} yr^{-1}	Average C stock[a] t C ha^{-1}	Period of observation	References
		0–30 cm	−0.20 ± 0.07	105.3	27 years	Schipper et al. (2014)
		0–90 cm	−0.36 ± 0.14			
Pastoral hilly land	New Zealand	0–30 cm	0.60 ± 0.16	104.8	27 years	Schipper et al. (2014)
		0–90 cm	0.90 ± 0.30			
Increase of temporary Pasture duration	France	0–30 cm	0.1 to 0.5 ± 0.24	51.6	20 years	Arrouays et al. (2002a,b)
Temporary to permanent grassland	France	0–30 cm	0.3–0.4	51.6	20 years	Arrouays et al. (2002a,b)
Moderate intensification, improved pasture	France	0–30 cm	0.2 ± 0.25	51.6	20 years	Arrouays et al. (2002a,b)
Planting of hedgerows	France	0–30 cm	0.1 ± 0.05	51.6	20 years	Arrouays et al. (2002a,b)
Annual cropping to perennials	Canada	0–30 cm	0.46 to 0.72	75	*20 years	VandenBygaart et al. (2008)
Conversion of annual cropland to grassland	USA (southeast)	0–25 ± 2 cm	0.84 ± 0.11	Not reported	17 ± 1 years	Franzluebbers (2010)
Conversion to improved grazing	USA	0–50 cm	0.41	40.1 ± 5.6	3–25 years	Conant et al. (2003)
Reseeded, grazed swards with N Fertilizer N applied at 0–500 kg N ha^{-1} yr^{-1}	Ireland	0–15 cm	1.04–1.45	Not reported	10 years	Watson et al. (2007)
Plantation & forestry						
Well-managed oil palm plantation	Indonesia	0–30 cm	0.42 ± 0.17	41.9	25 years	Khasanah et al. (2015)
Forestry	Indonesia	0–10 cm	1.12 ± 0.97	23.4	10 years	Dechert et al. (2004)
Afforestation	France	0–30 cm	0.44 ± 0.24	81	*20 years	Arrouays et al. (2002a,b)
Afforestation	Nigeria	0–15 cm	0.57	30	*35 years	Raji and Ogunwole (2006)
Afforestation	England	0–69 cm	0.54	59	120 years	Poulton et al. (2003)
Afforestation	England	0–69 cm	0.38	61	118 years	Poulton et al. (2003)
Afforestation	Taiwan	0–20 cm	0.34	22.9	23 years	Lin et al. (2011a)
Afforestation of grassland	Ireland	0–30 cm	2.2–2.5	97.2 ± 27.3	16 y	Black et al. (2009)
Afforestation on annual cropland – deciduous trees	USA	0–100 cm	0.35	51.8 ± 2.8	50 y	Morris et al. (2007)
Afforestation on annual cropland – coniferous trees	USA	0–100 cm	0.26	51.8 ± 2.8	50 y	Morris et al. (2007)

Numbers with * sign means C stock is based on regional estimates.

[a] Reported C stock prior to the management intervention.

[b] ± refers to standard error of estimates.

[c] Standard deviation.

effective C auditing schemes have now been developed that can be used to measure C stock changes at the farm scale (De Gruijter et al., 2016).

2.5. Tanzania

Leigh Winowiecki and Tor-Gunnar Vågen

Stocks of organic carbon to 0.3 m depth were calculated for Tanzania based on field survey data and MODIS reflectance data, producing a 500 m resolution digital soil map based on the methodology described in Winowiecki et al. (2016a) (Fig. 4). The largest SOC stocks were located in forested ecosystems around Mt Kilimanjaro and Mt Meru, in the Uluguru mountains south of Morogoro, parts of West Usambara mountains and in the south-eastern lowland (coastal) areas. This corresponds to previous studies that calculated 148 ± 53 t C ha^{-1} on average for top 0.3 m in the Uluguru mountains (Munishi and Shear, 2004) and 53.1 t C ha^{-1} up Mt. Hanang, reports (Swai et al., 2014). The West Usambara Mountains, for example, had high variability in SOC (ranging from 7.0–138 g kg^{-1}), with a 50% reduction of SOC in cultivated areas (Winowiecki et al., 2016b). No significant differences were found in carbon stocks to 0.3 m between the main land use classifications (woodland, shrubland, grasslands, and cropland). However, lowest SOC stocks were found on soils developed from granitic parent material and semi-arid climates, such as in Central Tanzania. These dryland areas have been experiencing increased population pressure as well as both agricultural and livestock expansion.

While variability across Tanzania was high, the mean estimated SOC stock to 0.3 m was calculated to be 47 t C ha^{-1}, which translates into a total of 4.44 Gt C as a whole (assuming an area for the country of 945,808 km^2). To achieve a 4 per mille increase, topsoil organic carbon would need to be increased by 17.78 million tonnes for the whole country. This number corresponds to 0.188 t C ha^{-1} year^{-1} increase. However, if we assume that only 33% of Tanzania is cultivated (312,116 km^2), and assuming that most of this increase will need to be on managed agricultural land, a 4 per mille increase corresponds to a 0.569 t C ha^{-1} year^{-1} increase.

In 2003, the Maputo declaration on Agriculture, Food Security in Africa was signed by nations who committed 10% of their annual budget to agricultural development. Furthermore, the confounding effects and uncertainty of climate change have resulted in the United Nations Framework Convention on Climate Change (UNFCC) supporting developed countries to develop national adaptation programme of action (NAPA). In line with the National Climate Change Strategy (2013), the Ministry of Agriculture, Livestock and Fisheries (MALF) in the United Republic of Tanzania prepared the Agriculture Climate Resilience Plan (ACRP) to identify and respond to the most urgent impacts posed by climate variability and climate change to crop productivity. This plan includes a suite of agricultural options, including climate-smart agriculture (CSA), which encourages increased soil organic carbon (FAO, 2013). While Tanzania is investing in sustainable agricultural intensification and CSA, research highlights that curbing land degradation (e.g., decreasing soil erosion, for example), has an important role in carbon sequestration, overall (Lal et al., 2015; Vågen and Winowiecki, 2013).

2.6. Indonesia

Yiyi Sulaeman and Budiman Minasny

The topsoil carbon stock estimate for Indonesian mineral soil (0–30 cm) based on soil legacy data and a soil map of 1:250,000 is 9.9 ± 0.4 Gt C with an average C content of 58 ± 2 t C ha^{-1}. The

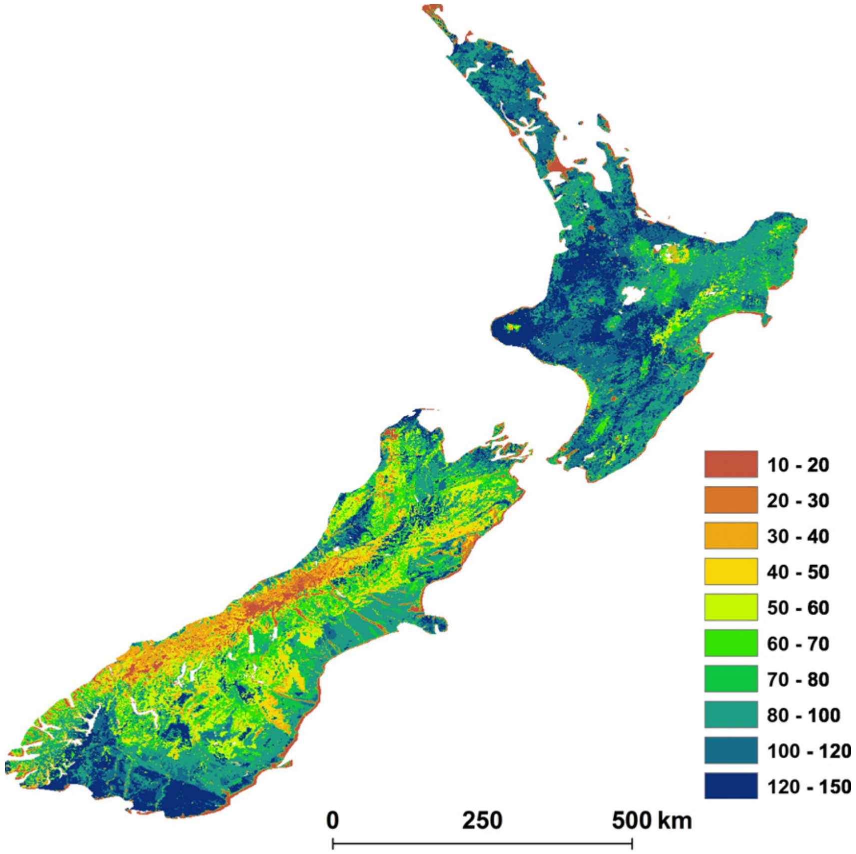


Fig. 3. Soil C stocks of topsoil (0–0.3 m) in t C $ha^{-1}$of New Zealand (New Zealand Agricultural Greenhouse Gas Research Centre, 2016), Map uses the Mercator projection.

estimate is based on soil order regardless of land use, with highest C content in Andisols (94 ± 2 t C ha^{-1}). SOC content was larger under wetland condition, lower pH, higher rainfall, higher altitude (lower temperature) and higher clay and silt content (van Noordwijk et al., 1997). Carbon stock for organic soils or peatland is estimated at 33.7 Gt C based on a peatland area of 20.9 Mha (Wahyunto and Agus, 2010). There is still a lot of uncertainty in these estimates as there is a lack of reliable spatial data on the peat extent and thickness (Page et al., 2010a, 2010b).

Although peat occupies only about 10% of Indonesia's land area, it holds more than twice the amount of C compared to mineral soils. In peats, organic matter accumulated under saturated conditions with a median accumulation rate estimated as 1.3 mm y^{-1} or 0.67 t C ha^{-1} $year^{-1}$ (Page et al., 2010a, 2010b). The carbon content in a well-developed peat is relatively constant at 550 ± 20 g kg^{-1} (Rudiyanto and Setiawan, 2016), with bulk density values ranging between 0.05 to 0.15 Mg m^{-3}. However, the thickness of peat varies considerably with the thickness of a peat dome can reach up to 20 m. Under natural saturated conditions, peat emits CO_2 and CH_4 gases due to anaerobic microbial activities.

The major processes of carbon loss from peatlands are enhanced decomposition from land use conversion and fire. Anthropogenic activities cleared and drained peatlands for the establishment of plantations or agricultural fields. These large-scale disturbances cause elevated CO_2 emissions. A study in Central Kalimantan showed a linear relationship between the average water table depth and C losses. The average C loss from the biological peat oxidation based on subsidence measurement is at 4.5 t C ha^{-1} $year^{-1}$ from a burnt peatland and 7.9 t C ha^{-1} $year^{-1}$ from a drained forest (Hooijer et al., 2014). Another study by Jauhiainen et al. (2012) who used heterotrophic respiration in an Acacia plantation on peatland in Sumatra found a value of 20 t C ha^{-1} $year^{-1}$. Despite variations in carbon losses found in various studies, these values demonstrate rapid carbon depletion in drained peatlands. Another problem with drained peat is that it subsides and can become hydrophobic, prolonged droughts during El Niño events can also aggravate peat fires. In the 1997 fire event on peatlands in Indonesia, it was estimated that 0.19–0.23 Gt C were released to the atmosphere (Page et al., 2002). In the 2016 fire event, it was estimated to release 0.48 Gt C (Global Fire Emissions Database, 2016) which is double the current amount of Indonesia’s greenhouse gas emission (excluding land use) of 0.21 Gt C.

In mineral soils, most studies have looked at soil organic matter depletion following the conversion from natural vegetation to plantations or agricultural lands (Leuschner et al., 2013). Smiley and Kroschel (2008) compared C stocks of cocoa agroforests in Central Sulawesi and found that C stock (0–1 m) decreased during the first 8 y, and increased after 9–15 years at a rate of 5.3 t C ha^{-1} $year^{-1}$. Another study by Van Straaten et al. (2015) compared SOC stocks from paired forests and adjacent oil palm, rubber, and cacao agroforest plantations from sites in Indonesia, Cameroon, and Peru. They found that SOC stock in oil palm, rubber, and cacao agroforestry plantations are up to 50% smaller when compared to natural forests. However, a study by Khasanah et al. (2015) in oil-palm plantations in mineral soils in Indonesia found no increase or decrease in soil C stocks compared with natural vegetation. Good practices which retain the plant residues can maintain soil C stock, and cause no detectable net carbon emission from soil at a scale relevant for national C accounting. These two contrasting results suggest that this space-for-time comparison must be interpreted with care, and there are different stages of the soil carbon “transition curve” (van Noordwijk et al., 2014) where plant and soil interactions are dynamic and both increases and decreases are possible.

This transition curve is demonstrated in a study using long-term soil legacy data from 1930 to 2010 on the island of Java (Minasny et al., 2011). This study showed that the topsoil SOC had a rapid decrease from 1930 (20 t C ha^{-1}) to 1970 (7 t C ha^{-1}), which is mostly due to the high conversion of forests and natural vegetation into plantations

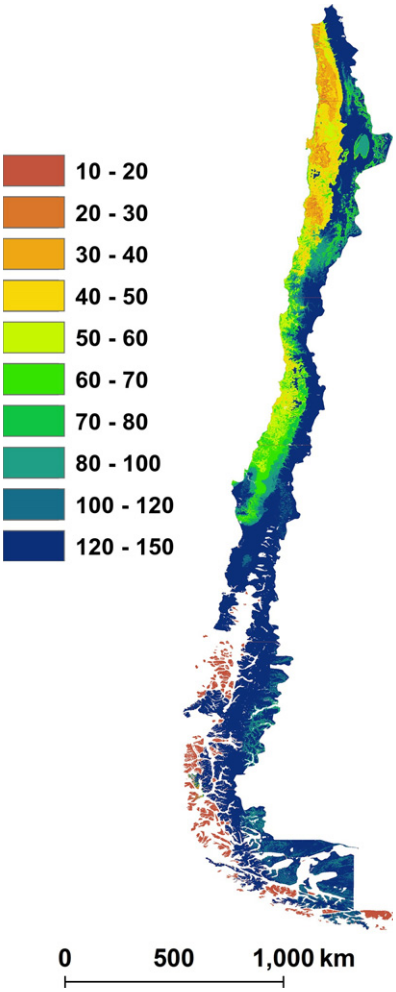


Fig. 4. Soil C stocks of topsoil (0–0.3 m) in t C ha^{-1} of Chile (from Padarian et al., 2016). Map uses the Mercator projection.

and subsequently to food crops. Conversely, there is a slow increase from 1970 to 1990 due to the green revolution and a further increase from 1990 to 2010. The increased biomass and the return of crop residues, green compost and animal manure application were mostly responsible for the rise of SOC content in Java, with a sequestration rate of 0.2–0.3 t C ha^{-1} $year^{-1}$. This finding gives rise to optimism for increased soil carbon sequestration in Indonesia.

The best strategy for SOC sequestration in Indonesia is to avoid deforestation for both mineral soils and peatlands, and restoring degraded lands. The government has been trying to resolve these issues nationally by establishing a peat restoration agency which aims to restore 2 million hectares of peatland within the next 20 years. In addition, it recently issued a moratorium on the suspension of permits for new oil palm plantation and land-mining development. At COP22 in Marrakech, the UN environment, government of Indonesia with partners around the world established the Global Peatlands Initiative with an aim to increase the conservation, restoration and sustainable management of peatlands in countries with significant peatlands.

Restoring degraded and deforested lands can lead to increase storage of soil carbon and restore soil's productivity and function. Degraded lands can be used for oil palm and forestry plantations. With no net increase in cultivated lands, the government has an important role in promoting good agricultural practices that increase crop production and also sequester soil carbon. Paddy soils have the greatest potential, straw incorporation with reduced inorganic fertilizer has been found to only increase soil carbon stocks but also crop yield (Sugiyanta, 2015). Planting high-yield varieties, balanced fertilization and organic fertilizer application, water management and crop care are some practices that can be applied. Andosols developed from volcanic ash have been found to have a high sequestration rate with a potential to store more carbon than mineral soils (Fiantis et al., 2016).

The 4 per mille initiative may not be applicable everywhere in Indonesia. In Indonesia, it should be aiming at neutral C emission from peatlands, and increasing soil C stocks in croplands. Most studies focus on measuring SOC loss (van Straaten et al., 2015), while we should now focus more on good data on soil management that can sequester SOC in Indonesia.

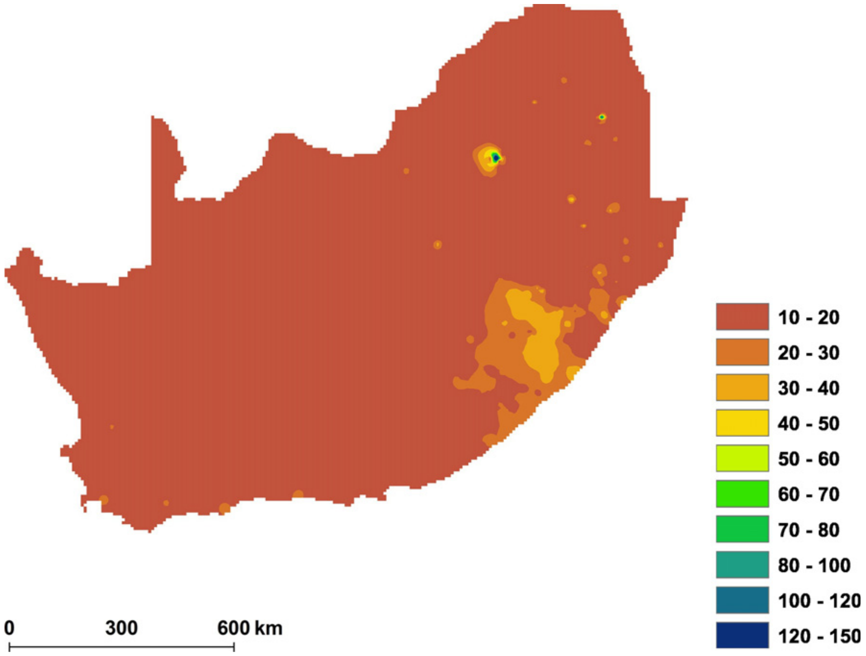


Fig. 5. A map of soil organic carbon (SOC) stock to 0.3 m in t C ha^{-1} interpolated over South Africa from 1433 observations using ordinary kriging. Map uses the Mercator projection.

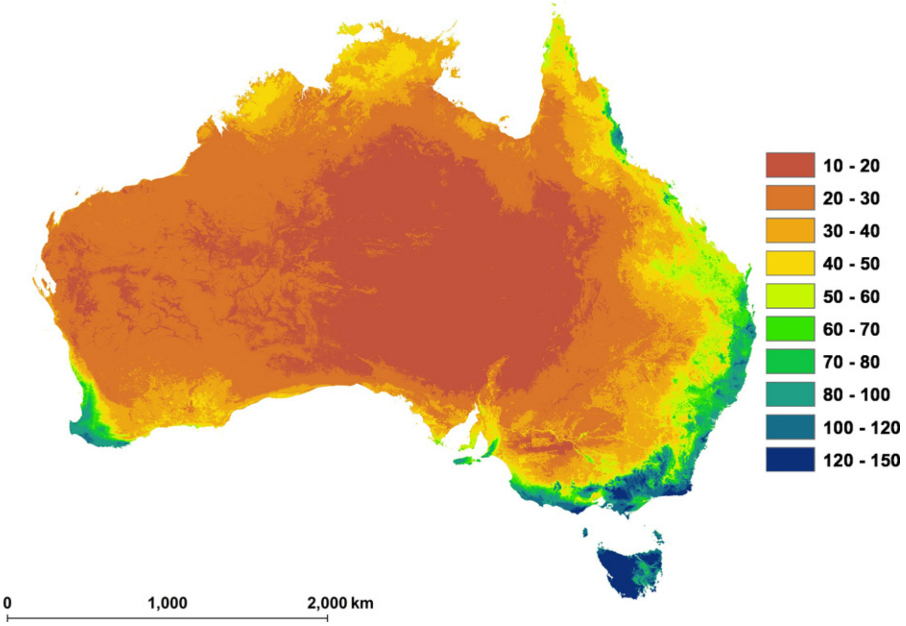
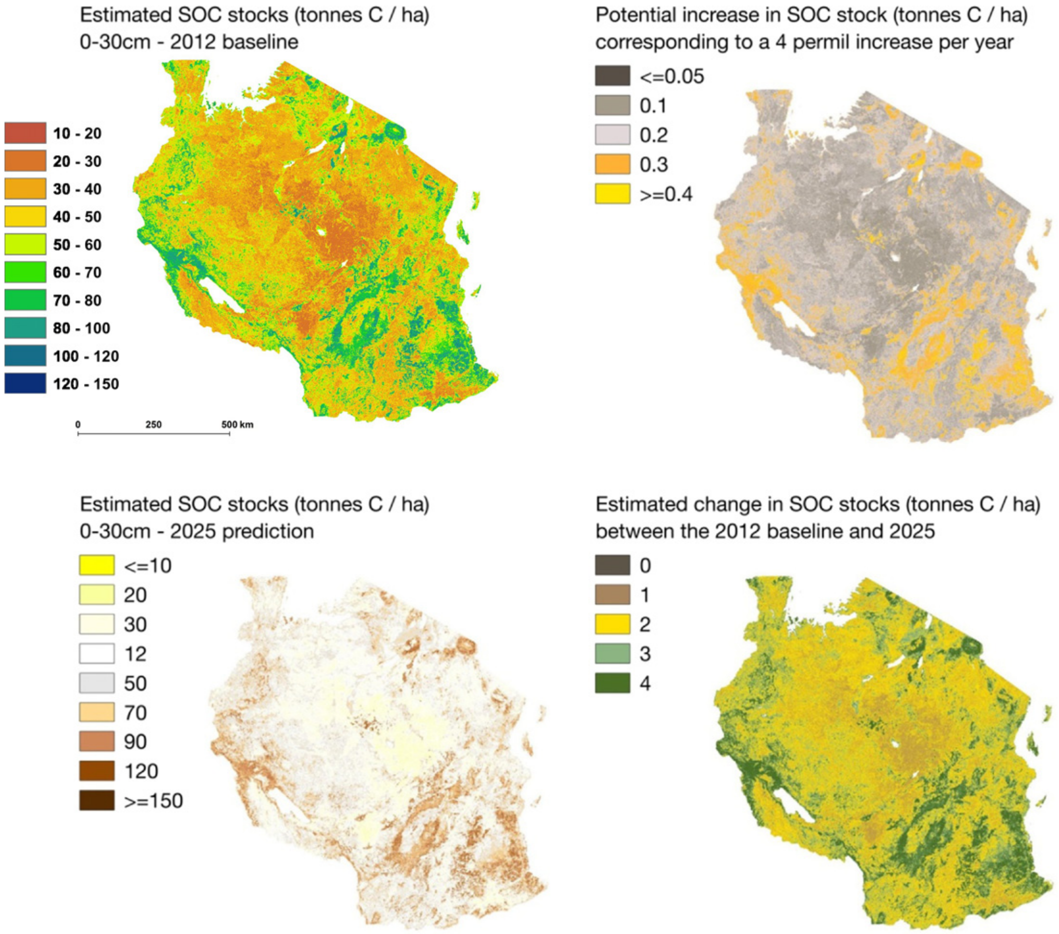


Fig. 6. Soil C stocks of topsoil (0–0.3 m) in t C ha^{-1}of Australia (data from Viscarra Rossel et al., 2014). Map uses the Mercator projection.


Estimated SOC stocks (tonnes C / ha) 0-30cm - 2012 baseline

Potential increase in SOC stock (tonnes C / ha) corresponding to a 4 permil increase per year

Estimated SOC stocks (tonnes C / ha) 0-30cm - 2025 prediction

Estimated change in SOC stocks (tonnes C / ha) between the 2012 baseline and 2025

Fig. 7. Map of SOC stocks to 30 cm at 500-m resolution (top left) for Tanzania. A targeted increase in SOC of four per mille per year would look like (top right). A map of predicted SOC stocks in 2025 if this target was met (bottom left) and the map on the bottom right is the difference between 2025 and 2012 under a scenario of 4 per mille increase.

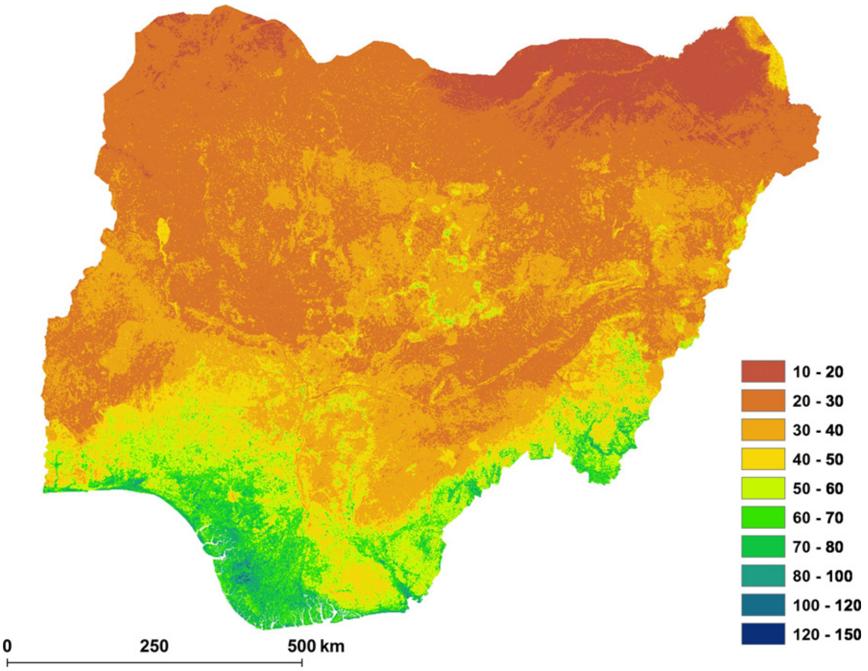


Fig. 8. Soil carbon stock of Nigeria for the top 0.3 m in t C ha^{-1}from Akpa et al. (2016).

2.7. Kenya

Tor-G. Vågen and Leigh Winowiecki

Kenyan soils store an estimated 2.4 Gt C in topsoils (top 0.3 m depth). These estimates were made based on a pantropical dataset of SOC concentrations and data on soil cumulative mass collected using the Land Degradation Surveillance Framework (LDSF) (Vågen and Winowiecki, 2013; Winowiecki et al., 2016a). Overall, estimated C stocks are lowest in countries that are part of the arid and semi-arid lands (ASAL) of Kenya, in the eastern and northern parts of the country,

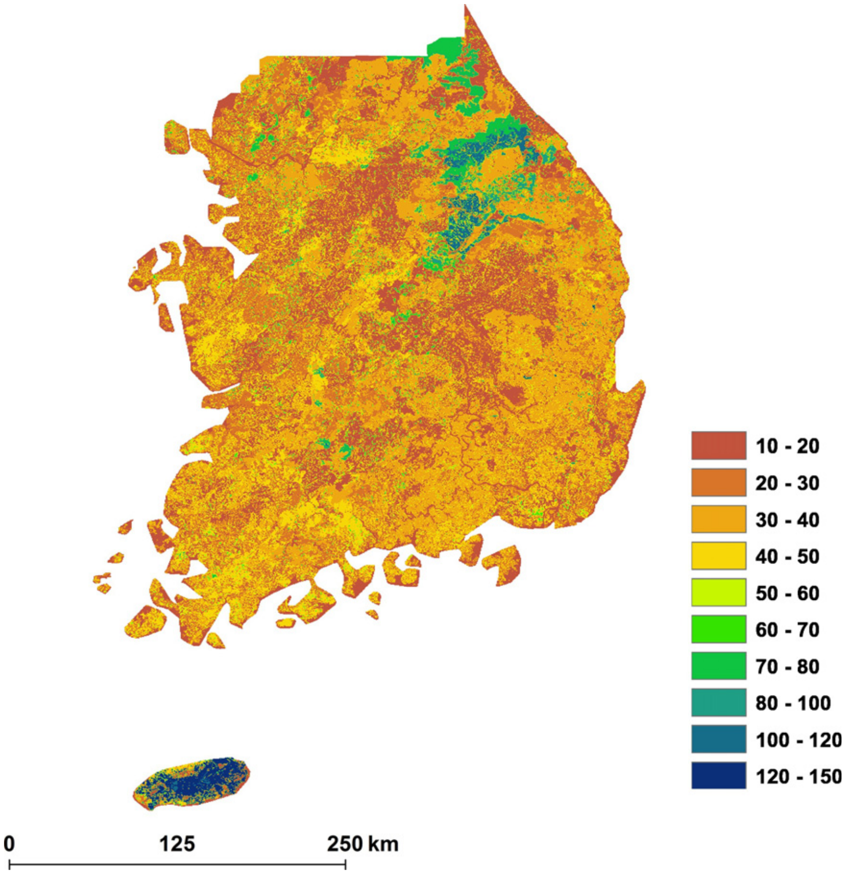


Fig. 9. Soil C stocks of topsoil (0–0.3 m) in t C ha^{-1}of South Korea (based on Hong et al., 2010). Map uses the Mercator projection.

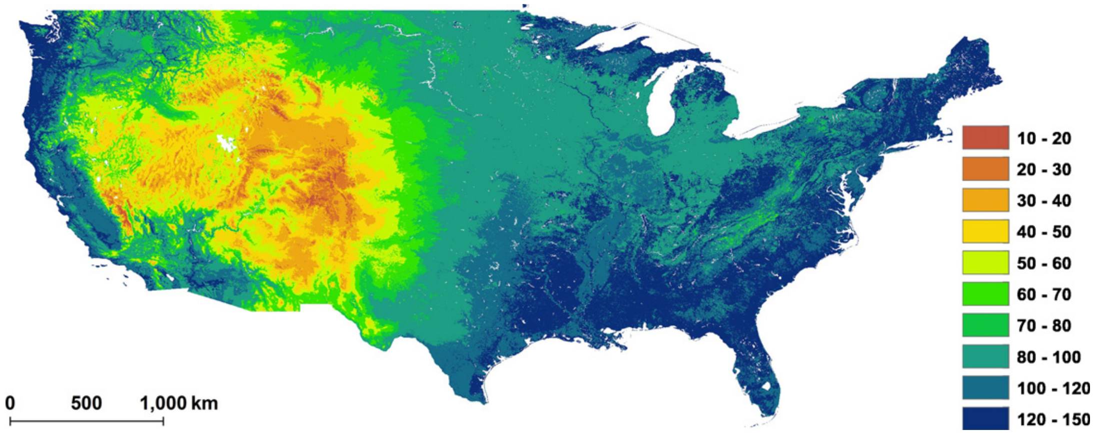


Fig. 10. SOC stocks of topsoil (0–0.3 m) in t C ha^{-1}of the USA. Data from Soil Survey Staff, Rapid Assessment of U.S. Soil Carbon (RaCA) project, USDA, NRCS. Map uses the Mercator projection.

particularly in areas with sandy soils. Higher values are found in subhumid and humid parts of the country, such as in the central highlands and in western region. The highest SOC stocks are found in forest systems, such as around Mt Kenya, the Aberdares, the Mau Forest Complex and Kakamega forest, as well as in wetland ecosystems. Inland riverine and palustrine wetland systems along for example the Ewaso Ng'iro River in Isiolo County are of critical importance for SOC storage in dryland ecosystems in Kenya. Carbon stocks in the top 0.3 m frequently reach between 80 and 100 t C ha^{-1}. Other wetland systems, such as around the Rift Valley lakes and lacustrine wetlands along Kenya's coast, are also examples ecosystems that are important for C storage in the country. Many of these wetlands are currently under threat in Kenya.

In order to increase SOC stocks in Kenya by 4 per mille, topsoil C would have to be increased by 9.6 million tonnes annually, which corresponds to about 0.17 t C ha^{-1} year^{-1} on average for the country. The total emissions of C from fossil fuels in Kenya were estimated at 10.79 million metric tonnes in 2006 and are likely to be higher in 2016, which means that emissions will be outpacing C storage rates with 4 per mille increases in SOC.

The potential for increased SOC storage is likely to be highest in parts of the country where water is not a major limiting factor, which are also the areas of the country that are most densely populated. Given these high population densities and the rapid expansion of agricultural lands in the country and the significant losses of SOC that result from cultivation (Winowiecki et al., 2016a), there will be a need for large-scale adoption of improved agricultural management, particularly practices that increase organic inputs to agricultural soils. Another important strategy will be to improve rangeland management to reduce overgrazing and soil erosion, which is also contributing to losses of C from the soil. While the potential to sequester SOC in rangelands — which are predominantly found in drylands — is limited when expressed on a per-unit-area basis they occupy very large areas and hence can play an important role for SOC storage in the country.

2.8. Nigeria

Inakwu Odeh

Apart from a few local and regional studies on soil carbon stock in Nigeria (e.g., Anikwe, 2010), there has been no formal coordinated national scale SOC inventory until a recent work by Akpa et al. (2016). Similarly, apart from a loose reference to enforcement of regulations for soil and water conservation, especially in erosion-prone areas in the National Vision 2010 (Ajayi and Ikporukpo, 2005) and to

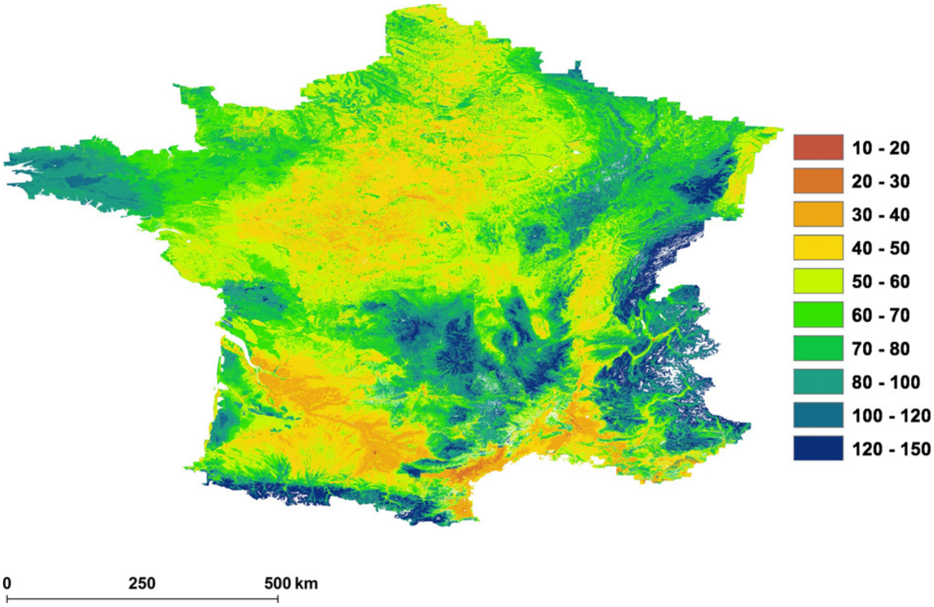


Fig. 11. Soil carbon stock of France for the top 30 cm in t C ha^{-1} (based on Mulder et al., 2016). Map uses the Mercator projection.

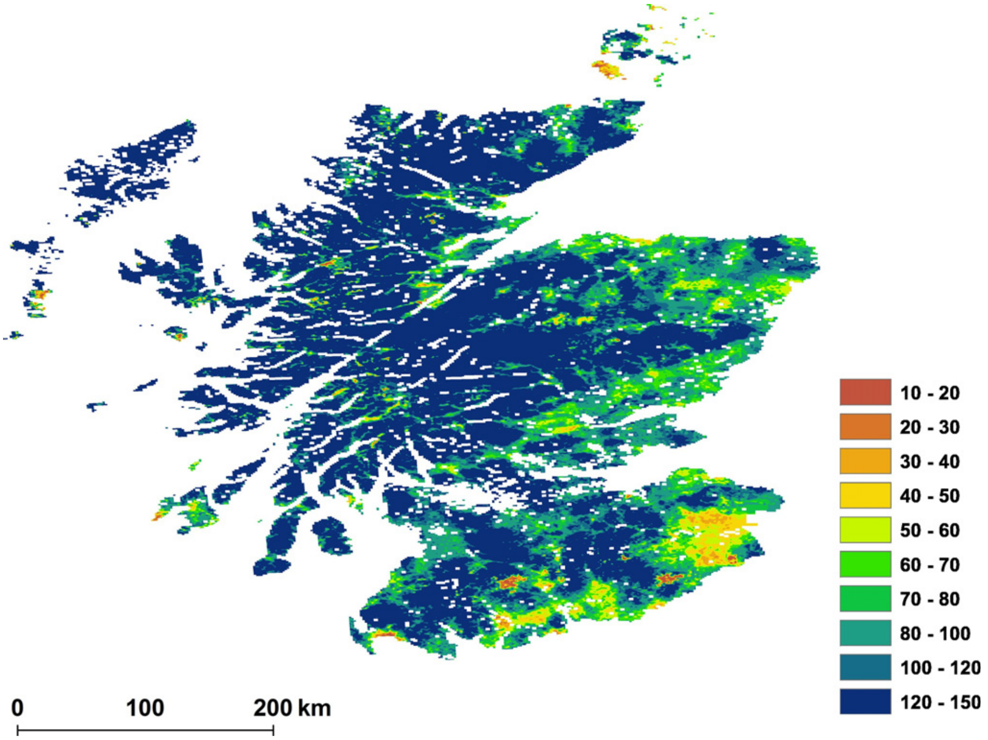


Fig. 12. Spatial distribution of carbon stocks (top 0.3 m) in t C ha^{-1} of Scotland according to the analysis of Poggio and Gimona (2014). Map uses the Mercator projection.

conservation agriculture for sustainable environment in Vision 2020, there has been no formal policy framework related to SOC or SOC monitoring in terms of a coordinated network of observations across the country.

The work by Akpa et al. (2016) was based on an assemblage of soil legacy data gathered over many years to enable the digital mapping of SOC. The digital soil map was created using the Random Forests algorithm based on the GlobalSoilMap specifications (Arrouays et al., 2014) and shows the spatial distribution patterns of SOC stock indicating a decreasing trend from the southern region to the north (Fig. 8). This trend has more to do with annual rainfall which decreases from over 3000 mm in the southern region bordering the Atlantic Ocean to about 500 mm in the north-eastern region bordering Lake Chad (Ilesanmi, 1971).

The study by Akpa et al. (2016) also indicated SOC density and stock in the top 0.30 m and 1.0 m to vary significantly across the different agro-ecological zones and land use types, with SOC density ranging between 20–60 t C ha^{-1} in the top 0.3 m and 47–118 Mg C ha^{-1} in the top 1 m. There was more SOC density in the Humid Forest zone than in any other zones. The distribution of total SOC stored in soils under the various agro-ecological zones ranged from 152 Mt in the Mid-High altitudes to 2035 Mt in derived savannah with values in other zones in between.

Given the differences in SOC stock across the prevailing land use types and agro-ecological zones in Nigeria, there is variable potential to sequester C (Akpa et al., 2016). As a consequence, the derived savannah zone which is transitional between the rainforest and savannahs zones has the highest capacity to store C (1.6 to 19.0 t C ha^{-1}), compared to other land use types. While the southern Guinea savannah (0.4 to 2.3 t C ha^{-1}) has the least capacity to store additional C. Under the humid forest zone, potential C sequestration rate ranged from 3.8 to 22.8 t C ha^{-1} with an average of 16.9 t C ha^{-1}. The restoration of shrubland, croplands, grassland, and savannah to native vegetation in each of these zones has the potential of storing an additional 3.8, 19.9 t C ha^{-1}, 21.1 t C ha^{-1} and 22.8 t C ha^{-1} respectively. These values represent a change of about 3.1%, 18.6%, 19.9% and 21.9% between the SOC in the current land use and the native vegetation (Akpa et al., 2016).

In terms of management of SOC under various farming systems and land management, results indicate that these are within the reported potential of soil to sequester C. For example, the work sponsored by the FAO (FAO, 2004) under drylands in northern Nigeria indicated that the rate of C sequestration with the use of legumes, fallow periods, farm yard manure and retention of plant residues varies between 0.1 and 0.3 t C ha^{-1} year^{-1}, over a period of 7 to 50 years. Comparatively, a study on the impact of afforestation on C sequestration under Guinea and Sudan savannah agro-ecological zones (Raji and Ogunwole, 2006) was reported to have resulted in a C sequestration rate of 0.57 t C ha^{-1} year^{-1} over 35 years.

2.9. India

Bhabani S. Das and Biswapati Mandal

The geographical location (between 8°4′ and 37°6′ N latitude and 68°7′ and 97°25′ E longitude), tropical and subtropical climates, predominantly dryland agriculture (~69% of total), and huge top soil erosion are the major reasons for inherently low (3.2 g kg^{-1}, on average) organic C content in Indian soils (Rai et al., 2009). Using the extensive database of the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), Bhattacharyya et al. (2008) estimated that Indian soils contain only 9.55 and 24.04 Gt organic C (SOC) out of about 13.69 and 46.50 Gt of total carbon in the top 0.3 and 1 m soil, respectively. Sreenivas et al. (2016) estimated SOC, soil inorganic C and total soil C pool size of India at 22.72 ± 0.93,12.83 ± 1.35 and 35.55 ± 1.87 Gt, respectively, in the top 1 m. Similarly, using modelling approaches, Falloon et al. (2007) estimated C stock for Indian soils in the order of 6.5–8.5 Gt; whereas Banger et al. (2015) reported the stock at 20.5 to 23.4 Gt. Thus, the Indian contribution to the global SOC pool is in the order of 20–25 Gt for the top 1 m. With an annual C emission of about 566 million tonnes from the Indian subcontinent (CDIAC database), the required C sequestration rate for India would be about 23–28 per mille as opposed to the global requirement of 4 per mille.

A closer look at the regional distribution of SOC stock across dominant agro-ecosystems in India showed that the semi-arid (116.4 Mha) and sub-humid (105.0 Mha) regions contribute to about 56% of the total SOC stock (Bhattacharyya et al., 2008). Forests (9.38 Gt) and mono- and double-cropped lands (8.81 Gt) contribute almost 80% to the total SOC stock (Sreenivas et al., 2016). Incidentally, Sreenivas et al. (2016) also observed the highest mean SOC density in soils under plantation (253 t C ha^{-1}) followed by forest (139.9 t C ha^{-1}) and agricultural land (58.5–67.4 t C ha^{-1}). Considering a declining forest area and availability of 147 Mha of degraded land (Maji et al., 2010) requiring immediate rehabilitation measures, an urgent attempt may be made to promote plantations in those lands for improving SOC stock in the country. Long-term experiments (25–40 y) with balanced fertilization (NPK) and 5–10 Mg ha^{-1} of organic residues in cropped land have shown an increase in SOC content by only 10–20% of the soil's initial value (Mandal, 2011; Pathak et al., 2011) ensuring a C build up rate of only 0.13 to 0.27 t C ha^{-1} $year^{-1}$ (equivalently, 0.043–0.089 Gt $year^{-1}$) under different rice-based cropping systems (Mandal et al., 2007, 2008). Lal (2004) also estimated C sequestration rates in India at about 0.024 to 0.036 Gt $year^{-1}$. More recently, Banger et al. (2015) estimated C sequestration rates to range from 0.027 to 0.045 Gt $year^{-1}$. Thus, with these prevailing C sequestration rates of 0.024 to 0.089 Gt $year^{-1}$ and about 25 Gt of SOC stock, it may be possible to contribute about 1–4 per mille SOC lost through C emission. Long-term experiments have clearly shown that to cause no depletion and maintain the SOC level, at least 0.31 to 5.16 t C ha^{-1} $year^{-1}$ are needed to be added to soils through crop residues or some other organic sources under different agro-ecological zones of the country depending primarily on the aridity index of the locations (Mandal, 2011). Promotion of pulses and legumes (for their unique SOC build-up properties), diverting a part of fertilizer subsidy and efficient use of available crop residues (679 Mt annually) and municipal solid wastes (64.8 Mt annually) along with green manuring and suitable cropping systems (rice-based) may help to improve or at least curb declining trends in SOC stock in Indian soils.

2.10. Taiwan China

Chun-Chih Tsui and Zueng-Sang Chen

Cultivated lands (0.8 Mha) and forest lands (2.1 Mha) are generally distinguished in China Taiwan with approximately 3.6 million ha in total. The estimation for total SOC stocks for the top 0.3 and 1.0 m are 38.5 and 77.0 Mt in cultivated soils (Jien et al., 2010), and 114 and 160 Mt (top 0.3 and 1.0 m) in forest soils (Tsai et al., 2010). The average SOC stocks of cultivated soils tend to decrease from north to south because of the warmer climate (Chen et al., 2000; Tsui et al., 2013). For forest soils, the variation of SOC stocks is significantly related to air temperature and elevation gradients. The current annual CO_2 emissions from fossil fuel of Taiwan are 251.04 Mt (or 68.47 Mt C).

In general, 49.6% of cultivated lands are used for rice production, which is more efficient for C sequestration compared to other crops (Chen et al., 2000). Rice-cropping systems combined with applications of compost and crop residues have been strongly recommended by government agencies. Since there is no regular monitoring network for cultivated soil carbon, SOC sequestration rates of various practices in cultivated soils were estimated based on limited long-term studies. If we consider that the upper 0.3 m of soils weigh 4,000 t ha^{-1}, then the annual SOC sequestration rates are 0.46 t C ha^{-1} $year^{-1}$ with synthetic fertilizer application and 0.83 t C ha^{-1} $year^{-1}$ for organic farming (Wei et al., 2015a, 2015b). Therefore, 0.74 to 1.33 Mt C $year^{-1}$ can be sequestrated in cultivated soils of China Taiwan. If we use the estimated SOC stocks for topsoil as 152.5 Mt, then the annual increase rate of SOC is 0.61 Mt (0.21 t C ha^{-1} $year^{-1}$) to meet the 4 per mille challenge. The results indicated that SOC sequestration rates of various practices in cultivated topsoil (0.46 to 0.83 t C ha^{-1} $year^{-1}$) are much higher than the 4 per mille goal estimated for China Taiwan.

Afforestation in the marginal crop lands of plains has been positively implemented since 2002. The government agencies plan to afforest 25,000 ha. The annual SOC sequestration rate in the top 0.3 m in the afforested lands is estimated at 0.51 t C ha^{-1} $year^{-1}$ (Lin et al., 2011a, 2011b). We estimated the annual increase rate of SOC in the topsoil of natural forest land to be at least 1 t C ha^{-1} $year^{-1}$ for natural vegetation ecosystems of the subtropical monsoon region of Taiwan. Therefore, 2.10 Mt of SOC can be sequestrated in forest topsoils of China Taiwan.

The Taiwan Agriculture Research Institute (TARI) has conducted a detailed soil survey based on a grid sampling design (250 m × 250 m) between 1992 and 2010. More than 130,000 pedons from the surface to 1.5 m were collected from the cultivated soils. There was also a detailed survey for forest soils (>8,000 pedons) which was conducted by Taiwan Forestry Research Institute (TFRI) between 1993 and 2002. We hope this will improve the SOC stock calculation in China Taiwan in the near future.

2.11. South Korea

Suk Young Hong

The SOC stock (to 1 m) for South Korea based on 390 soil series and the associated 1:25,000 soil series map is estimated at 447 Mt, with an average SOC density of 50 t C ha^{-1}. The topsoil (0–0.3 m) holds half of the C stock. SOC stocks in grass and agricultural lands were as large as 88 and 68 t C ha^{-1}, respectively (Hong et al., 2010). SOC storage of agricultural land in Korea is approximately 174 Mt (to 1 m). About two-thirds of the land is mountainous covered by forest with steep slopes and shallow soils. Intensive agriculture is mainly established on the plains. The South Korean government has agricultural policies on food security which ensures self-sufficiency and price stability for rice. Farming in South Korea is highly intensive and synthetic fertilizers were subsidised up to the year 2005. Agricultural land constitutes about 23% of the land area in the 1970s (2.23 Mha), but due to rapid industrialization and increasing population, its size has been shrinking. In 2015, the area is estimated as 1.68 Mha, with a decreasing rate of 14,400 ha y^{-1}. The agricultural sector also has been decreasing in both the gross national product and employment rate (Jo and Koh, 2004).

A national soil monitoring program was established in 1999 for major agricultural lands in South Korea, including paddy fields, upland agriculture systems, orchards, and plastic-film houses. Samples have been collected every four years, and analysis of these data showed that there has been an increase in the mean topsoil (0–0.2 m) organic carbon content from 11.3 g C kg^{-1} in 1970 to 12.8 g C kg^{-1} in 1999, to 13.2 g C kg^{-1} in 2003 (Minasny et al., 2012). The calculated mean rate increase is 0.17 g C kg^{-1} $year^{-1}$ or 0.43 t C ha^{-1} $year^{-1}$. For upland soils, the mean increase calculated from 131 soil series from 2001 to 2005 is 0.39 g C kg^{-1} $year^{-1}$ or 0.64 t C ha^{-1} $year^{-1}$. Nevertheless, a recent analysis using the more recent soil test database showed that the SOC level in paddy soil is stable at around 13 g C kg^{-1} (Minasny et al., 2016).

There has been a great concern in the recent decades on agricultural sustainability in Korea which relies heavily on synthetic fertilizer and accelerates soil erosion. In 2010, the Korean government halted chemical fertilizer subsidy, but continued to subsidise organic fertilizer. Balanced fertilizer management was promoted to reduce environmental impacts and the storage of carbon and nitrogen in agricultural soils. A long-term fertilizer trial showed the benefits of adding compost and compost with inorganic fertiliser in increasing SOC stock (Lee et al., 2013). The application of compost and return of rice straw is encouraged.

Although there is a potential to sequester carbon in Korean soils, the shrinking and limited agricultural land areas will not be able to offset its greenhouse gas emission. 4 per mille on the agricultural land will only sequester 0.7 Mt C while it emits more than 170 Mt C annually. Nevertheless South Korea has a 2030 target of reducing greenhouse gas emissions by 37 percent from business-as-usual (BAU) levels using technologies, renewable resources and a carbon tax.

2.12. China Mainland

Kun Cheng and Genxing Pan

The total SOC stock for the upper meter of soil was estimated at ~ 90 Gt for 870.94 Mha covered by 2473 soil series surveyed from the 2nd National Soil Survey conducted in the early 1980s. The SOC pools of farmland, forest and grassland were 12.98, 34.23 and 37.71 Gt, respectively (Xie et al., 2007; Yu et al., 2007). The total SOC pool in the top 0.3 m was estimated to account for 54% of the carbon stock in the top 1 m (Wang et al., 2004). The average C density for agricultural soils is 83.4 t C ha^{-1} in top 1 m and 41.6 t C ha^{-1} in the top 0.3 m. China's topsoil SOC stock is about 44 Gt, but only 5.1 Gt C stored in croplands (1.3 Gt C in rice paddies and another 3.8 Gt in dry croplands) (Pan et al., 2010).

Conservation tillage, which involves minimum tillage plus straw return had been applied on only 1.5% of China's cropland by 2009 (Ministry of Agriculture of China, MOA, National Development and Reform Commission of China, NDRC, 2009). According to the National planning of conservation tillage project of China (2009–2015) (Ministry of Agriculture of China, MOA, National Development and Reform Commission of China, NDRC, 2009), 17% of cropland in the north of China would participate in the conservation tillage project by 2015, and the expected SOC concentration in plough layer would be increased as 0.1–0.6 g kg^{-1} annually.

However, in the last decade, Chinese cropland has received fertilizers with unbalanced nutrients, particularly excess N and without proper straw return or organic amendments. National projects such as “Work program of popularization operation of recommended fertilization” aim to reduce N use and to balance nutrients, mainly with combined organic and inorganic fertilizers. Since 2005, 60 Mha of cropland across China's mainland had been covered under this project until 2008 (Ministry of Agriculture of China, MOA, 2009). According to national plans (Ministry of Agriculture of China, MOA, 2009, 2010, 2011), the area under this project will increase by 6.67 Mha each year from 2009 onwards and will eventually cover all cropland within 20 y. There is also a national program that provides a subsidy to encourage farmers to return crop straw, increasingly apply organic manure, and plant green manure. “Straw Comprehensive Utilization Project” was established by the government of China since 2008. The recent straw utilization rate was about 80%, and this rate is projected to increase to more than 90% by 2020.

According to the “National plan of high standard farm construction”, there will be as much as 40% of China's cropland considered as farms with a high standard. One of the important indicators is that the SOC concentration of these farms should be at least 12 g kg^{-1}. The mean SOC concentration of China's dry cropland was only 10.8 g kg^{-1}, although 74% of rice paddies had the SOC concentration higher than 12 g kg^{-1} (Pan et al., 2010; Cheng et al., 2013).

The “National Cropland Monitoring Network” was established since the 1980s, and consisted of more than 300 observation sites including dry croplands and rice paddies. A previous study indicated that most of the sites (79%) showed an increase of SOC in the past 20 years (Cheng et al., 2009). A more recent study showed that a mean increase in topsoil C (0–0.2 m) stock was estimated to be 25.5 Mt C year^{-1} or 0.20 t C ha^{-1} year^{-1} between 1985 and 2006, with a total topsoil C stock increase of 0.64 Gt C over 21 years (Pan et al., 2010).

Given the estimates for the SOC stock top 1 m, the required national sequestration rate according to 4 per 1000 is 360 Mt year^{-1}, corresponding to 0.41 t C ha^{-1} year^{-1}. For croplands, the SOC stock in the top 1 m was 13–15 Gt with an average C density of 83–85 t ha^{-1}, accordingly the required sequestration rates would be over 50 Mt year^{-1} or over 0.35 t C ha^{-1} year^{-1}. The C stocks in dry croplands and rice paddies were 10.1 Gt (80 t ha^{-1}) and 2.9 Gt (986 t ha^{-1}), indicating required sequestration rates of 40 Mt year^{-1} (0.33 t C ha^{-1} year^{-1}) and 12 Mt year^{-1} (0.39 t C ha^{-1} year^{-1}).

Most of studies on C sequestration in China focused on the plough layer (0–15 cm for rice paddies and 0–20 cm for dry croplands) (Xie et al., 2007). Table 1 lists the main management practices that are found to be beneficial to sequester carbon in soil in China. In general, the carbon sequestration rates varied from 0.2 to 0.8 t C ha^{-1} year^{-1} under different practices. The rates were higher than 0.33 t C ha^{-1} year^{-1} (required by 4 per mille) under most practices except for no tillage. However, the projected SOC sequestration potential was usually lower than 50 Mt year^{-1} mainly because there is still work to be done to expand best management practices in China. Furthermore, the understanding of carbon sequestration in deep soil which may make a considerable contribution is still limited.

Areas that can potentially contribute to sequestration are in north and northwest and southwest China where low soil C density was observed (Song et al., 2005; Cheng et al., 2013). In addition, there was a fast decrease of SOC density in northeast China in the past two decades which made them susceptible to erosion under intensive dryland agriculture (Cheng et al., 2009; Sun et al., 2010). Wang et al. (2015) indicated that soils from the Heilongjiang Province in northeast China could represent a carbon gap, where the C input from the straw returns is inactive.

Improvement of soil organic matter stock has been shown to benefit soil productivity and ecosystem services for China's agriculture (Pan et al., 2014). Reinforcing soil organic matter in croplands has been adopted as a long term action in the national strategy to protect soil health as well as to recycle biomass wastes in agriculture (Ministry of Agriculture of China, Reform and Development Commission of China, Ministry of Science and Technology of China, Ministry of Financing of China, Ministry of Land Resource and Territory of China, Ministry of Environment Protection, Ministry of Water Resources of China and National Bureau of Forestry of China, 2015). For this, a state funded national project was launched in 2016 (Ministry of Agriculture of China and Ministry of Financing of China, MoAC, and MFC, 2016) to enhance the return of crop residues through direct or indirect treatment approaches, among which biochar from straw pyrolysis had been taken into account for increasing soil organic matter in croplands rapidly from North and Northeast China where organic matter has been commonly depleted.

2.13. United States of America

Keith Paustian and Adam Chambers

The US has a great diversity of agricultural production systems spanning a wide range of soil and climatic conditions, making it among the world's largest in terms of both production and land area. Consequently it also produces significant emissions of GHGs from the sector; it's currently estimated that agriculture emits 142 Mt C from all sources combined, overwhelmingly as CH_4 and N_2O, principally from livestock and soil nutrient management (USEPA, 2015).

The potential for US cropland and grassland soils to act as a significant C sink has been discussed for over two decades (e.g., Barnwell et al., 1992; CAST, 2011; Lal et al., 1998; Paustian et al., 1997) and a number of studies have estimated the potential magnitudes for different land uses and changes in practices and policies and using different estimation methods. Most have quantified so-called technical potential, in terms of known practices and mechanisms, assuming deployment of best-management-practices for promoting soil C increases, independent of economic or policy constraints. Aggregate potential estimates are on the order of 50–100 Mt C year^{-1} for US cropland (Lal et al., 1998; Sperow et al., 2003; Sperow, 2016) and 15–70 Mt C year^{-1} for grazing lands (Conant et al., 2002; Follett et al., 2001, Schuman et al., 2002). It is notable that the majority of these aggregate estimates are several years old and mainly based on first-order methods of average per ha C accrual rates applied to regional or national-scale area totals of available land area. New assessments with more spatially disaggregated data and dynamic models could provide more refined and informative estimates, particularly if coupled to economic models to assess adoption rates as a function of C prices and impacts on net economic returns.

A variety of existing practices that promote soil C sequestration, via increased C inputs to soil and/or increased stabilization of organic residues in soil, can be more widely applied on US cropland and grasslands (CAST, 2011). Practices on croplands include higher residue crops, increased perennials in rotations, reduced and no-till tillage, cover crops, reduced summer fallow frequency, organic amendments such as manure, compost, biochar (if accounted for on a life cycle basis), conservation plantings (buffer strips, riparian buffers, windbreaks, shelterbelts) and conversion of marginal cropland to grassland or wooded set-aside. Grazing land practices include improved grazing systems, legume additions, improved nutrient management and silvapastoral systems. There are a relatively large number of long-term field experiments across the US that provide data on rates of soil C change from adopting these practices and a number of reviews and meta-analyses that characterize and summarize these rates have been published (e.g. Paustian et al., 1997; Ogle et al., 2005; CAST, 2011; Denef et al., 2011; Franzluebbers, 2005; Johnson et al., 2005). However research gaps exist, including limited field data for some practices, underrepresented geographic areas and less data for deeper (>30 cm) soil horizons (Paustian et al., 2016).

With respect to the 4 per mille initiative, the aspirational goals of increasing soil C stocks, providing a sink for CO_2 as well as promoting increased soil health, are in keeping with the US Department of Agriculture (USDA) Climate Change Mitigation Building Blocks and various soil health and conservation programs promoted by USDA's Natural Resources Conservation Service (NRCS). Chambers et al. (2016) suggest that a 4 per mille increase goal could be achieved when using the current C contents in the top soil (0–20 cm) on managed croplands and grazing lands as the reference stock. That soil C stock, estimated at ca. 17.5 Gt C (USEPA, 2015), would imply a target of ca. 68 Mt C year^{-1} of net sequestration by 2025, which if compounded annually at 0.4% would reach 75 Mt C year^{-1} by 2050. Achieving these rates with currently recommended soil management practices would require adoption on 25–70% of total US cropland (145 Mha in 2013), varying depending on the combinations of practices and their geographic distribution. Adoption of C sequestering practices on grazing lands could reduce the contribution needed from cropland (Chambers et al., 2016).

Achieving this level of C sequestration would require a greatly increased investment, either from public or private sources. On average about 4 Mha of cropland and 8 Mha of grasslands would need to be enrolled each year, for the next decade, in projects or programs with effective C sequestering practices. In addition, significant investments would be need to monitor, evaluate and adjust these programs over time, requiring a long term commitment to ensure that soil conditions and climate mitigation benefits are attained.

2.14. France

Dominique Arrouays, Manuel Martin, Anne C. Richer-de-Forges, and Vera Leatitia Mulder

Soil organic carbon estimates for different depth layers (0–5 cm, 5–15 cm, 15–30 cm, 30–60 cm, 60–100 cm and >100 cm) were recently made at 90-m resolution for mainland France, along with their upper and lower confidence intervals (Mulder et al., 2016). The maps were developed using the GlobalSoilMap specifications (Fig. 11, Arrouays et al., 2014). The total SOC stock for mainland France was found to be 6.91 Gt. The majority of carbon was stored in the top 60 cm (5.14 Gt, 74%) of which 3.56 Gt (51%) was stored between 0–30 cm, 1.58 Gt (23%) was stored between 30 and 60 cm and 1.77 Gt (26%) was stored below 60 cm of which 12% below 1 m. Concluding, roughly 49% is stored in the sub and deep soil layers; these findings demonstrate that the SOC stocks in these layers significantly contribute to the total SOC stock for France.

SOC is monitored in France at the national level using a systematic network grid (16 km by 16 km; Arrouays et al., 2002a). However, as there has been only one campaign of measurements, it is still an inventory. The second campaign of measurements will begin in 2016. Another source of data is the French soil test database (e.g., Angers et al., 2011; Arrouays et al., 2012; Saby et al., 2008) in which soil tests required by farmers have been stored from 1990. Nowadays, results from more than 2 million samples are available, which allows a reliable calculation of changes (e.g., Saby et al., 2008; Orton et al., 2012a; Chauveau et al., 2014). Most of the changes from 1990 until now were decreases, mainly attributable to changes in land use over the intervening decades.

If we base our estimates on the total area of mainland France (about 500,000 km^2 excluding urban area), reaching the 4 per mille objective would mean a sequestration rate of 26.6 Mt C year^{-1} on the whole soil depth, or 14.4 Mt C year^{-1} for 0–30 cm. This rate of storage represents 0.55 t C ha^{-1} year^{-1} for the whole depth or 0.28 t C ha^{-1} year^{-1} for the topsoil. The latter sequestration rate should be achievable through changes in land use and agricultural practices (Arrouays et al., 2002b; Métay et al., 2009). Carbon sequestration in deep soils in heterogeneous landscapes is complex due to the different driving factors (Mulder et al., 2015) and so the potential of C sequestration in deep soil still remains unknown.

Areas of SOC sequestration potential have been identified (Angers et al., 2011; Mulder et al., 2015) they are mainly located in intensive cropping areas, such as in Northern France and in the Southwest, and in vineyards and orchards. We believe that the 4 per mille rates are feasible mainly in the cultivated areas of France that are about 20 millions of hectares (Arrouays et al., 2002b). The potential of additional sequestration in forests and grasslands remains more uncertain (Arrouays et al., 2002b; Soussana et al., 2004). However, we must stress that 4 per mille is a finite solution in time and space for climate change mitigation and that long-term solutions to decrease greenhouse gas emissions should remain among the policymakers' priorities.

2.15. Belgium

Bas van Wesemael

Soil C stock in Belgium has been estimated from different studies: Meersmans et al. (2011) for cropland in Flanders (the northern part), Lettens et al. (2005) for forest in Flanders and Wallonia (the southern part) and the methodology of Goidts and van Wesemael (2007) for cropland and grassland in Wallonia. This approach is also followed in the National Inventory report (NIR, National Inventory Report, 2016) where the areas under the different land use types are given. The topsoil (0–0.3 m) C stock amounts to 215 Mt (108 Mt for agricultural land) and to 1 m, 319 Mt (164 Mt for agricultural land). There is a general north-west (North Sea coast) to south-east (Ardennes) increase in C stocks corresponding to an increase in mean elevation with associated decrease in temperature and increase in precipitation. The C stocks are therefore highest in the Ardennes where croplands are limited and the climate conditions favour forest and grassland. The C density in the topsoil ranges from 48 t C ha^{-1} in croplands on Luvisols in the central loam belt to 113 t C ha^{-1} in grasslands on stony Cambisols on the plateau of the Ardennes.

A 4 per mille increase in topsoil C across the whole area corresponds to an annual amount of 0.86 Mt – about 0.28 t C ha^{-1} year^{-1}. Given the density of the population and the economic activity in a small country like Belgium, it is not surprising that the GHG emissions in 2013 were an order of magnitude larger (32.6 Mt C year^{-1}) than a potential 4 per mille increase of topsoil C (0.86 Mt year^{-1}). In order to achieve the 4 per mille of topsoil SOC sequestration on the 1.63 million ha of agricultural land, an average of 0.53 t C ha^{-1} year^{-1} (0.88 t C ha^{-1} year^{-1} for cropland only) would be required. Such sequestration rates are unrealistically high compared to the ones found in other European countries (Table 1).

Belgium has a detailed soil map produced from 1950 to 1970, and an extensive legacy data set of 13,000 analyzed profiles. Recent SOC monitoring is based on a re-sampling of ~600 of these profiles in 2005 and 2013 and the use of soil fertility test samples. In the long term (1960–2005), croplands have lost SOC at rates of 0.016 t C ha^{-1} $year^{-1}$ in Flanders and 0.06 t C ha^{-1} $year^{-1}$ in Wallonia, while grasslands have lost 0.019 t C ha^{-1} $year^{-1}$ in Flanders and gained 0.1 t C ha^{-1} $year^{-1}$ Wallonia. These differences are explained by changes in agricultural practices such as drainage of grasslands in valley bottoms and increase in organic amendments by intensive livestock breeding (van Wesemael et al., 2010). The first results for the period 2005–2013 in Wallonia show that the SOC in cropland has increased again at rates of 0.6 t C ha^{-1} $year^{-1}$, probably as a result of the widespread introduction of winter cover crops. Walloon grasslands continue to slightly increase their SOC stocks by 0.16 t C ha^{-1} $year^{-1}$ (NIR, National Inventory Report, 2016). Carbon contents reach critical values of less than 1 % in croplands of the loam belt in the middle of the country (~0.26 million ha), leading to the loss of aggregate stability, surface crusting and muddy floods after heavy rainfall. These are the areas with the greatest sequestration potential. Intensive livestock breeding in the north has resulted in an excess of N and P contents in most soils, therefore, the possibilities of using external input of organic matter are very limited by strict manure regulation. Agriculture is less intensive in the south-east (Ardennes) dominated by grasslands. However, SOC contents are already large and slightly increasing, and hence, the additional sequestration potential is limited.

2.16. England and Wales

Ben Marchant

Bradley et al. (2005) estimated that in 1990 the total organic carbon stocks in the top 1 metre of soil in England and Wales were 1.74 Gt and 0.34 Gt respectively. These figures correspond to average densities of soil organic carbon of 133 t C ha^{-1} and 164 t C ha^{-1}. Therefore, to increase these stocks by 0.4% to this depth each year would require annual sequestration of 0.534 t C ha^{-1} in England and 0.656 t C ha^{-1} in Wales or an average rate of 0.55 t C ha^{-1} across the two countries.

Soil policy documents for the UK such as ‘Safeguarding our soils – a strategy for England’ (Defra, 2009), the ‘Natural Environment White Paper’ (Anon, 2011) and the ‘Soil Health’ report of the Environmental Audit Committee (House of Commons Environmental Audit Committee, 2016) highlight the need to protect and enhance soil carbon stocks. The white paper aims to reduce the annual consumption of peat by the horticulture industry in England from 2.4 million cubic metres to zero by 2030. This would equate to an annual saving of more than 0.1 Mt of carbon per year (Milne and Brown, 1997). However, the majority of the stocks of carbon in peat are found in Scottish rather than English or Welsh soils (Milne and Brown, 1997). The ‘Safeguarding our Soils’ document acknowledges that further research is required to determine the best methods to boost soil carbon stocks.

Bhogal et al. (2009) reviewed best practice for managing soil organic matter in lowland agriculture. Conversion from tillage systems to permanent grassland, the introduction of woodland, growing biomass crops and the introduction of rotational grass could all lead to substantial initial carbon sequestration rates but the stocks would settle to a new equilibrium after 50–100 y. These practices would also lead to a loss of agricultural production and would require financial incentives for land owners. Bhogal et al. (2009) also noted that reductions in soil erosion, better tillage and additions of organic matter had the potential to enhance soil carbon stocks but further work was required to quantify the benefits of these approaches on different soil types.

The majority of studies investigating the extent to which land management practices can enhance soil carbon stocks have used long-term experiments such as the Rothamsted Classical Experiments (Blair et al., 2006) which tend to be conducted on relatively productive soils. Powlson et al. (2012) reviewed the results of UK studies and found that a change from conventional to reduced tillage could increase carbon stocks by 0.31 ± 0.18 t C ha^{-1} $year^{-1}$ and that the addition of biosolids to soils at the maximum rate permitted in UK Nitrate Vulnerable Zones (S.I., 2008) could lead to annual increases in SOC of 0.63 t C ha^{-1} $year^{-1}$ for farm manures, 1.5 t C ha^{-1} $year^{-1}$ for digested biosolids and 1.4 t C ha^{-1} $year^{-1}$ for green compost. Typical applications of cereal straw and paper crumble could lead to annual increases of 0.375 t C ha^{-1} $year^{-1}$ and 1.8 t C ha^{-1} $year^{-1}$ respectively. However, they warned that these benefits were unlikely to be realised since (i) many farmers were practicing rotational tillage and any carbon gains from reduced tillage could be lost during the ploughing phase (ii) the management changes might lead to increased N_2O emissions which could counteract the carbon benefits (iii) the benefits would disappear with time as the carbon stocks reached a new equilibrium (iv) farmers were already applying biosolids to soils so these were not wholly new benefits (v) the biosolids might only be available locally as the by-products of specific industries and (vi) the reported gains in carbon might merely reflect its redistribution between different depths. Similarly, Mangalassery et al. (2014) emphasised the importance of taking a holistic view of the fluxes of greenhouse gasses when estimating the benefits of zero tillage. Powlson and Johnston (2015) estimated that a switch from continuous arable farming to ley farming could increase carbon stocks in sandy and silty clay loam soils by up to 0.2 t C ha^{-1} $year^{-1}$ but this of course would be at the cost of reduced arable production.

Whitmore et al. (2015) reviewed novel technologies that could be used to increase soil carbon storage. They concluded that some of these such as (i) the use of polyphenols to complex carbon or inhibit the enzymes that decompose it, (ii) the use of the methods of physical protection that operate in the subsoil in both the topsoil and subsoil and (iii) mineral carbonation all have potential for widespread application and reasonably rapid benefits. However, these technologies are not sufficiently developed for the potential benefits to be quantified.

Any soil carbon sequestration that is achieved should be verified through soil monitoring. There are two national-scale soil monitoring networks with coverage across England and Wales that have been sampled more than once. The National Soil Inventory (Bellamy et al., 2005) and the Countryside Survey (Reynolds et al., 2013) both observed declines in carbon stocks within arable soils between the late 1970s and the 2000s but there are no plans to conduct further phases of these surveys (House of Commons Environmental Audit Committee, 2016). These surveys only consider topsoils and Gregory et al. (2014) conclude that there is very little evidence of whether subsoil stocks are changing.

2.17. Ireland

Sharon O'Rourke

Total land area in Ireland is 6.9 million ha. The national C stock is estimated as 2.824 Gt for mineral soil and peat soil to depths greater than 1 m (Khalil et al., 2013). Including all land use types (arable, forest, grassland, heterogeneous agricultural area, peatland, suburban and wetland), topsoils are estimated to contain 0.888 Gt C and soils to a depth of 1 m, 1.832 Gt C. Spatial distributions of soil C stocks show the highest soil C densities (1000 to >1500 t C ha^{-1}) reflect raised bogs that stretch from the Midlands up through the north-west region. Higher altitude along the western seaboard produce blanket peat of C between 250 and 1000 t C ha^{-1} and uplands on the East Coast >250 t C ha^{-1}. The majority of mineral soils have between 100 and 250 t C ha^{-1}, but in the Midlands soil C densities are low, up to 100 t C ha^{-1}, where podzols or shallow brown earths dominate (Tomlinson, 2005).

Focusing on agriculture and forestry land covers, 5.3 million ha is grassland, arable (4.3 and 0.4 million ha, respectively; Khalil et al., 2013) and forest (0.5 million ha; Eaton et al., 2008) land use. Soil C stock is estimated as 728 Mt in the top 0.3 m and 1306 Mt in the 1 m depths (Khalil et al., 2013; Eaton et al., 2008). An increase of 4 per mille in soil C stock translates into an increase of 2.9 Mt C year^{-1} or about 0.5 t C ha^{-1} in topsoils. If soil depth to 1 m is considered, 5.2 million tonnes of soil C is required to meet the national target or double the rate per hectare at 1.0 tonne year^{-1}. In the most recent greenhouse gas inventory report (Duffy et al., 2015), CO_2 emissions from the energy sector (fossil fuel emissions) were estimated at 35 Mt C year^{-1}. The resulting ratio of C emissions over soil C stock is 3% and 5% for the two soil depths, 10-fold the global rate.

Irish agriculture is predominantly grass-based. The second largest GHG emissions sector (32.2 %) after the Energy sector (60.8 %), GHGs are projected to increase a further 7 % (between 2014 and 2020) assuming growth targets for agri-food, fisheries and forestry are achieved. An appraisal of carbon-neutrality for Irish agriculture proposes an 'accelerated sequestration' pathway based on the mechanisms; (1) enhancing C sequestration rates in grasslands, (2) stimulating C sequestration in permanent arable soils and (3) planting of new forests, involving land use change (Schulte et al., 2013). In general, it is assumed that grassland and forestry are carbon sinks, cropland is carbon neutral while peatland/wetland is a C source.

Achievable sequestration rates in Ireland indicate the 4 per mille rate is possible (i.e. 0.6, 0.4 and 0.6 t C ha^{-1} year^{-1} for grassland, arable and forestry, respectively). Ireland already has relatively high soil C concentrations, ranging from 32 to 63 g kg^{-1} (Kiely et al., 2010; Xu et al., 2011) and for well-managed swards C sequestration can vary between 1.1 and 1.4 t C ha^{-1} y^{-1} (Watson et al., 2007). Management options (i.e. zero-tillage, conversion to permanent crops, the addition of slurry or FYM) typically yield 0.4 to 0.6 t C ha^{-1} year^{-1} in arable soils (see Smith et al., 2005). Afforestation on mineral soils is dependent on previous land use and soil type. For example, afforested pasture suggests a significant loss of soil C in brown earth soils, whereas grey/brown podzolic and particularly gley soils accumulate soil C (Black et al., 2014). Afforestation of grassland has achieved 2.2 to 2.5 t C ha^{-1} year^{-1} over the first 16 y of rotation (Sitka Spruce on gley soils) dropping to 0.2 t C ha^{-1} year^{-1} after 16 y (Black et al., 2009). Less the opportunity to increase C stocks but rather to mitigate C losses is to prevent further drainage of high organic C soils. Peatland/wetland is considered a C source due to widespread historical (pre-1990) drainage of organic soils (O'Reilly et al., 2012).

In Ireland, LULUCF is reported under the Tier 1 method (IPCC, 2006). The Irish Soil Information System has recently produced a new complete map of soils in Ireland. It is hoped that a revision of the attribution of soil type and soil C, and land use will produce Tier 2 country specific values for soil C stock and management factors in the coming years. Until revised soil C stocks are made available it is difficult to ascertain critical limits of soil C stock.

2.18. Scotland

Laura Poggio and Alessandro Gimona

Scotland's soils are very diverse, from mineral alluvial soils to peats with different pressures and demands, especially in the context of climate change. In Scotland, the area with the capability to support intensive agriculture is likely to expand (Gimona et al., 2015, Brown et al., 2011), and therefore soil carbon might decline where land use is converted to arable. Peatlands can act as a source or sink of carbon depending on their condition. Peatlands that are cultivated for agriculture can release as much as 6.5 t C ha^{-1} year^{-1}. Peatlands, in good condition, however, retain their stored carbon and can sequester around 0.2 to 0.8 t C ha^{-1} year^{-1} (Artz et al., 2014). Scotland has about 60% of the UK's peatlands and 4% of Europe's total peat carbon store (UKCC, UK Committee on Climate Change Adaptation Sub-committee, 2011). Today around 1.8 million ha (over 20% of Scotland's land area) is covered by blanket bogs alone (JNCC, Joint Nature Conservation Committee, 2011). Their condition, therefore, will be a key for their ability to increase total carbon stocks in Scotland.

Different estimates of Scottish soil carbon stocks exist based on different methods, e.g. a traditional approach (Chapman et al., 2013, Lilly and Baggaley, 2013), a machine learning (Aitkenhead and Coull, 2016) and a hybrid generalised additive model (GAM) geostatistical 3D model (Poggio and Gimona, 2014). While considering the geostatistical approach (Fig. 12) the average stock is 429 t C ha^{-1} (3.14 Gt) of which 300 t C ha^{-1} (0.704 Gt) in mineral soils, 461 t C ha^{-1} (1.57 Gt) in organo-mineral and 561 t C ha^{-1} (0.8 Gt) in organic soils. However, there is a rather large modelling uncertainty around these values even without considering different estimates due to different approaches. The traditional and geostatistical approaches (Baggaley et al., 2016) were compared providing similar estimates with spatial differences especially when considering the uncertainty.

Given that Scottish soils are in general carbon-rich, to achieve a 4 per mille increase in C sequestration, the soil carbon stock would need to be increased by 12.56 Mt (about 1.7 t C ha^{-1} year^{-1}). This seems like a very ambitious target for Scottish soils (see e.g. Smith et al., 2010) especially if the predicted expansion of agricultural land, due to climatic amelioration, is realized (Gimona et al., 2015). Scotland has numerous policies for soil and peat conservation and to increase carbon stocks to mitigate climate change (e.g. The Scottish Soil Framework, The Land Use Strategy). In order to move towards the 4 per mille goal, policies need to be implemented to manage contrasting demands and pressures, such as reducing peatland degradation, forest, and agricultural expansion.

2.19. Canada

Denis A. Angers and Brian G. McConkey

Canada has a total land area of 998.5 Mha which contain 72.2 Gt of C to a depth of 30 cm (Tarnocai, 1998). A total of 55.2 Mha of land is currently used for agriculture which contains about 4.14 Gt C to a depth of 30 cm and 5.5 Gt to 100 cm. As about 80% of agricultural land is located in the Canadian Prairies, most (approximately 88%) SOC is also found in Prairie soils, which are mostly (C-rich) Chernozemic soils developed under grassland.

Based on an extensive national network of long-term field experiments and a long history of applied and fundamental research, Canada has developed a deep understanding of the nature and dynamics of the organic C of its agricultural soils, their spatial distribution and response to management practices. Several management practices have been shown to increase SOC such as reducing summer fallowing, adopting no till, including more perennial crops in the rotations, returning crop residues, improving degraded lands, etc. Many of these management practices may result in gain varying from 0.1 to 0.5 t C ha year^{-1} (VandenBygaart et al., 2003, 2008), which is in the range of values corresponding to a 4 per mille increase in SOC. So the 4 per mille increase is indeed achievable locally in Canada. However, these effects vary with soil and climatic conditions. For example, no till may have a lower potential to store SOC in eastern Canada than in the Prairies (VandenBygaart et al., 2003).

Canada estimates that agricultural lands currently (the year 2013) remove 11 Mt of CO_2 which represents about 2% of the total national GHG emissions (Environment Canada, 2015). This is largely due to a reduction in the use of summer fallow and increases adoption of no-till in the Canadian Prairies. However, the removal of CO_2 through soil C sequestration is starting to decline (down from 13 Mt in 2005 for example) as the legacy effects of these practices are starting to decrease and a new equilibrium is reached.

The idea that degraded soils probably offer the greatest potential for SOC improvement, and would also be those that would benefit most from it, is central to the concept of the 4 per mille initiative. Based on the indicator of state and trends for soil organic matter for Canada (Cerkowniak and McConkey, 2016), we estimated that of the 55.2 Mha of land currently used for agriculture, 4.2 Mha are severely degraded and 12.3 Mha are moderately degraded with respect to SOC.

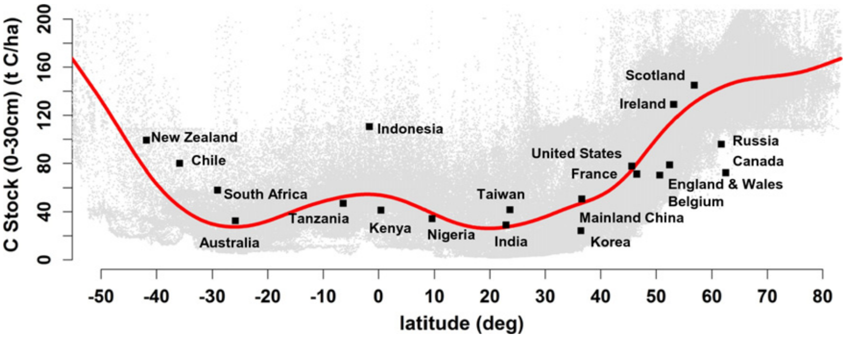


Fig. 13. Soil C stock (0–30 cm) as a function of latitude. Grey dots are data from the global soil carbon map (Fig. 2). Black squares are reported soil C stocks for regions in this study plotted on their centroid latitudes.

Changes in agricultural practices are estimated to be increasing SOC on 1.4 and 8.9 Mha of those severely and moderately degraded soils, respectively. Therefore, the lands with the greatest potential and priority for improved land management practices to reduce further SOC loss and actually increase SOC are the 2.8 Mha of severely degraded soils and 3.4 Mha of moderately degraded soils where SOC is not estimated to be increasing. This represents about 11.2% of Canada's agricultural land. There is additional 5.0 Mha of land where SOC is not considered degraded but are currently estimated to be losing SOC. There are opportunities to reduce and reverse the SOC loss on this 9.1% of Canada's agricultural land. There would be limited opportunities to further increase SOC on the remaining 79.7 % of Canada's agricultural land without fundamental changes to land use or type of agricultural production.

2.20. Russia

Igor Savin and Vladimir Stolbovoy

The soils of Russia store 164 Gt C in the top 0.3 m, and 292 Gt C in the top 1 m. The currently observed rise in temperature and precipitation in Russia leads to a sequestration rate of 72 ± 32 Mt C annually in the soils of tundra, forest-steppe, steppe, and semi-desert natural zones (Stolbovoy and Ivanov, 2014).

The arable and pasture soils occupy about 12% of the country containing 16.8 Gt C in the upper 0.3 m and 28.0 Gt C in upper 1 m. Historically, agricultural practices have resulted in the loss of 2.6 Gt C on croplands and 0.5 Gt C on pastures in the top 0.3 m (Stolbovoi, 2003). The total loss of C from 0.3–1.0 m is about 1.5 Gt C. The conversion of cropland into grasslands and forests since 1990 caused sequestration of 0.8 Gt C. Thus, the total potential C-sink of agricultural soils is about 3.6 Gt C with reference to the baseline of C pool under natural ecosystems in Russia. In relation to the 4 per mille target, the agricultural soils should accumulate 4.4 Mt C, which corresponds to the sequestration rate of 0.16 t C ha^{-1} year^{-1} for cropland.

Nearly 85% of the C loss in Chernozems and Kastanozems is caused by cultivation. The loss can be compensated by crop selection, implementation of crop rotation with grasses and legumes, multiple uses of crop residues, application of organic fertilizers, precision farming, etc. About 15% of C loss is caused by soil erosion, which can be regulated by minimizing runoff, conservation tillage etc. All above-mentioned measures will be enough to achieve the 4 per mille target in Russia.

Russia has a long tradition to maintain C balance in agricultural soils such as C-conservation crop rotations, application of organic fertilizers, liming etc. The current C-related land policy includes State Monitoring of Agricultural Land and Criteria of Soil Fertility Depletion. In addition, there are many State technical regulations concerning protection and conservation of C content in soils. The Ministry of Agriculture of Russia has a special program for soil fertility (including soil C content) monitoring. In the framework of this program, one-fifth of agricultural soils in Russia is observed yearly.

3. Discussion

Soil carbon has a high spatial variation with increasing variation from field to regional, continental, and global extent (Kerry et al., 2012; McBratney and Pringle, 1999; Scharlemann et al., 2014). SOC stock fluctuates with latitude and longitude with greater stocks at higher latitudes, decreases in the mid-latitudes, and increases in the humid tropics (Fig. 13). The high value in the humid tropics (e.g. Indonesia) is due to the high precipitation (Marín-Spiotta and Sharma, 2013) and net primary production (Baccini et al., 2012). While, the high SOC content at high latitudes corresponds to the low temperature regimes.

We examined SOC sequestration potential from 20 countries and regions to provide a global snapshot of soil carbon conditions. Most countries are optimistic on the 4 per mille initiative and showed efforts and scopes for soil carbon sequestration. Lal (2016) posed some challenges for the 4 per mille initiative, including: paucity of scientific data, the finite capacity of soil carbon sinks, permanence, resource-poor farmers and small landholders, financial commitments, and implementation. These challenges are also reflected in the case studies. Here, we discuss several general potentials and challenges emerging from the regional narratives, summarised in Table 2.

3.1. Not all lands can sequester carbon

Table 1 is a compilation of potential and actual SOC sequestration rates after the adoption of best management practices from various regions in the world. Some data are based on long-term experiments, some are inferred from the literature, and thus there is a certain amount of uncertainty in these data. Most reported sequestration rates are from the top soil or plough layer (0–0.3 m, or even only to 0.1 m).

The 4 per mille initiative was based on a blanket calculation of the whole global 2 m profile C stock, which amounts to an annual sequestration rate of 9.6 Gt C. However the potential to increase SOC is mostly on managed agricultural lands. If we consider top 1 m of 3900 to 4900 Mha of global agricultural land, its SOC stock estimate is between 480 to 790 Gt, and 4 per mille of this stock is 1.9-3.1 Gt C. This effectively can offset between 20–35% of global GHG emissions. Fig. 2 shows an estimate of global topsoil SOC stock distribution.

Table 2 lists SOC stocks in agricultural areas and also the potentials and limitations in the regions. The 4 per mille targets agricultural lands to increase their sequestration rate. Some countries (e.g. Australia) have large agricultural areas with great potential to increase SOC stock, while in other countries, the total area available for cropping is limited (e.g. Belgium, S. Korea). In regions with high inherent SOC content, it may prove difficult to further increase their C levels, as these areas may already have reached equilibrium with current practices. Conversely, in regions with low (inherent) SOC (e.g. India), it can also be difficult to increase the C content, as high temperature enhances decomposition, and the removal or burning of crop residues are still

Table 2

A summary of soil organic C stocks in different countries/regions and the potential and challenges in implementing the 4 per mille initiative. The table is arranged by the country's centroid latitude.

Country/region	Centroid latitude	Total land area (Mha)	Total soil organic C stock 0–30 cm (Gt)	Agricultural area (Mha)	Soil C stock in agricultural land (Gt)	Potentials	Challenges
New Zealand	−41.814	26.8	2.66	15.1	1.59	Improved management of grasslands; increased root inputs of C; targeting specific soil types (e.g. allophanic soils), and/or specific landscape positions; establishment and reestablishment of wetlands.	Inherently high C soils, C loss in drained peats, overgrazing, soil erosion in upland areas when converted to pasture.
Chile	−35.816	69	5.52	3.2	0.14	Afforesting degraded areas and conserving native forest and peatlands	Peatland conversion, limited cropping areas
South Africa	−29.051	121.3	7.03	115	6.68	Improved practices on rangeland (savannahs and natural and semi-natural grasslands)	Land degradation on rangelands
Australia	−25.848	769	25	455	12.76	Large agricultural land area, optimization of crop rotations, and retention of crop residues, improved grassland management.	Lack of water, zero or minimum tillage has been implemented almost 80% in the grain cropping areas.
Tanzania	−6.396	94.5	4.44	31.2	1.39	Adoption of improved agricultural management practices and land restoration options. Technologies to reduce soil erosion.	Land degradation, intensification pressure and converting marginal land into agricultural/cropland
Indonesia	−1.656	190	Mineral: 9.9 Peat (whole profile): 33.7	60	Mineral: 3.0[a]	Avoid deforestation, Paddy rice with straw return, well-managed plantation.	C loss in drained peats and fire. Very little data on C sequestration potential.
Kenya	0.422	58.1	2.4	17.8	0.76	Adoption of improved agricultural management practices and land restoration options. Technologies to reduce soil erosion.	SOC loss due to rapid expansion of agricultural lands, converting marginal land into agricultural/cropland.
Nigeria	9.585	91	3.12	29	0.97	Use of legumes, fallow periods, plant residues retention, afforestation	Lack of reliable data
India	22.932	328.7	9.55	147	3.15	Plantations on degraded lands, return residues on cropping area, promotion of pulses.	Inherently low C soils, moderate to high rainfall and high temperature.
China Taiwan	23.645	3.6	0.15	0.8	0.038	A high sequestration rate under best management practices	Topography limits area for cropping, lack of C sequestration rates
South Korea	36.448	9.2	0.223	2.24	0.087	Paddy fields with balanced fertilisation and straw return can sequester soil C.	Decreasing and limited agricultural lands.
China Mainland	36.591	959.7	48.6	528	27.4	Conservation tillage and straw return, balanced fertilization.	Lack of C sequestration data on subsoil, not all cropping areas are under best management practices
United States of America[b]	45.625	702	54.5	436	30.3	Improved crop rotations, cover crops and reduced bare fallow, conservation tillage, improved grazing systems, set-aside of marginal lands	Incentivizing producers, more limited options in arid and semi-arid regions
France	46.531	50	3.56	30	1.95	Soil carbon monitoring network allows C gain and loss to be calculated, changes in land use and best agricultural practices	High soil sealing rate by urbanisation and infrastructures
Canada	62.50	998.5	72.2	55.2	4.14	Reducing summer fallowing, adopting no-till, including more perennial crops in the rotations, returning crop residues, improving degraded lands	Further development and implementation of innovative land use and management practices to improve degraded land.
Belgium	50.662	3.05	0.215	1.63	0.108	Improve management in degraded croplands	A small area with high population density, additional sequestration may not be feasible in areas that are already high in SOC
England & Wales	53.163	13.04 2.08	England: 1.0 Wales: 0.19	England: 8.9 Wales: 1.8	England: 0.82 Wales: 0.11	A large proportion of well-managed agricultural land where carbon sequestration strategies can be applied.	Expansion of intensive agriculture, requires more evidence about the long-term effectiveness of carbon sequestration strategies for a range of farming systems and soil types
Ireland	53.887	6.9	0.89	5.3	0.73	Enhancing C sequestration rates in grasslands, stimulating C sequestration in permanent arable soils and planting of new forests	Drainage of organic soils, lack of soil C sequestration data, forestry expansion competes with grass & arable land
Scotland	56.400	8	Total: 1.16 Peats (up to 1 m): 0.8	5.6	0.33	Reducing peatland degradation, forest, and agricultural expansion	A large area of peatlands, expansion of intensive agriculture
Russia	61.699	1710	164	205	16.8	Best management practices on croplands, conversion of cropland into grasslads and forests	C loss through cultivation.

[a] Estimates based on percentage of agricultural land.

[b] Total areas are sum of cropland, pasture/hay, rangeland and forest in the conterminous 48 states from the 2010 USDA Natural Resource Inventory survey; agricultural land area excludes forest land area. SOC stocks are from the 2013 USDA Rapid C Assessment.

frequently practiced. The effort here is to make sure that a critical C input is required to maintain the SOC stocks (net change = 0) (Mandal, 2011).

Organic soils pose a vast problem in many countries (Chile, Scotland, Ireland, New Zealand, and Indonesia). The C content in peats is mostly not going to increase by 4 per mille even under natural conditions. The challenge is to ensure that these areas are carbon neutral with efforts in restoration of natural vegetation in peatlands.

3.2. Management strategies

It has been established that there are management techniques which facilitate build-up of organic matter (Table 1, see also Paustian et al., 2016). Although sequestration rates varied between countries and climatic conditions, there is a trend on types of management and SOC accumulation rates: afforestation (~0.6 t C ha^{-1} $year^{-1}$), conversion to pasture (~0.5 t C ha^{-1} $year^{-1}$), organic amendments (~0.5 t C ha^{-1} $year^{-1}$), residue incorporation (~0.35 t C ha^{-1} $year^{-1}$), no or reduced till (~0.3 t C ha^{-1} $year^{-1}$), and crop rotation (~0.2 t C ha^{-1} $year^{-1}$).

Reported SOC sequestration rates generally show that under best management practices, 4 per mille or even higher sequestration rates can be accomplished. Data from Table 1 drawn on Fig. 14 indicated that there is a tendency of a higher C sequestration potential (10–30 per mille) on croplands with low initial SOC stock (topsoil ≤30 t C ha^{-1}). Sequestration rates on grasslands which already have a high initial SOC stock (topsoil >60 t C ha^{-1}) are limited to 4 per mille. In addition, the number of years after management practices have been applied is also important (Fig. 15). The data show that within the first 5 years sequestration rate can be up to 20 per mille, after 20 years up to 10 per mille, and after 40 years limited to 4 per mille.

Reduced or conservation or no tillage has been one of the most important land management systems that sought to increase SOC (e.g. Lal, 2003). Many researchers reported significant increases in topsoil carbon stocks under reduced tillage practices in combination with crop residue retention. In addition, conservation management practices also reduce direct emissions through lower use of fuel, and improved soil physical, chemical, and biological properties. However, the benefit of soil C stock increase has now been scaled back as it has been widely observed that SOC stocks do not necessarily increase under reduced tillage methods when greater soil depths are investigated (Baker et al., 2007; Du et al., 2017; Dimassi et al., 2014; Piccoli et al., 2016; Powlson et al., 2014; VandenBygaart and Angers, 2006). The calculated increases in carbon stocks under reduced tillage were largely based on topsoil or plough layer (Baker et al., 2007). When SOC at deeper depths is accounted for (>40 cm), studies have shown that there is no significant difference between reduced and conventional tillage (Blanco-Canqui and Lal, 2008, Piccoli et al., 2016; Powlson et al., 2014). Nevertheless, studies such as by Syswerda et al. (2011) from a long term-experiment in Southwest Michigan, USA, found that although there were no significant differences in SOC at depth, and the C gains in the surface soils of no-till were not offset by change at depth. In addition, SOC at depths spatially is more variable making such statistical inference more uncertain (Syswerda et al., 2011). There are also other obvious benefits of reduced tillage beside SOC stocks, i.e. the quality of organic matter, enhanced structural stability and increased microbial diversity and activities (Devine et al., 2014; Palm et al., 2014; Piccoli et al., 2016). A recent review by Zuber and Villamil (2016) showed that microbial biomass and enzyme activities were greater under no-till compared to tillage.

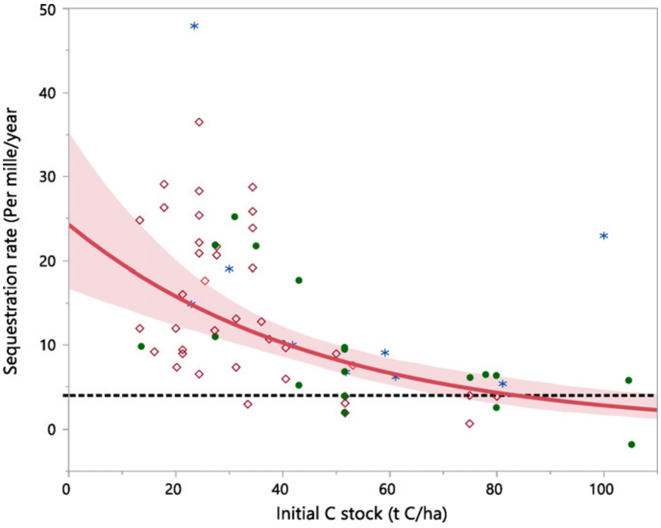


Fig. 14. Initial soil C stock and reported per mille sequestration based on studies in different regions reported in Table 1. The red curve is a regression model fitted to the data, the shaded areas are the 95% confidence interval of the model, the dotted line is the required 4 per mille, red diamonds refer to cropping land, green dots are grassland, and blue stars are forestry/plantation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In the context of soil carbon to mitigate climate change, there is a consensus that SOC sequestration is only "true" if management practice causes an additional net transfer of C from the atmosphere to land (Powlson et al., 2011). SOC accrual could be just an avoided emission, when compared with conventional management techniques (Sanderman and Baldock, 2010). Afforestation and conversion of arable land to pasture at its initial stage leads to the highest SOC sequestration rate as evidenced globally. This constitutes "true" sequestration according to Powlson et al. (2011), as soil's initial condition under cropland has a much smaller C stock. Pasture in particular has a higher root to shoot ratio. However, converting croplands to forest or grassland will reduce food production, additional GHG (N_2O and CH_4) emissions related to the grazing ruminant animals, adding to the pressure of the required increase in food production. There is a suggestion that afforestation or pasture conversion should be strategized to least productive areas or re-vegetation of degraded lands (Powlson et al., 2011). Improving pasture management on overgrazed grasslands also leads to higher SOC sequestration (Badgery et al., 2014).

Plantation crops are usually blamed for losing soil carbon (van Straaten et al., 2015), however best management practices on these

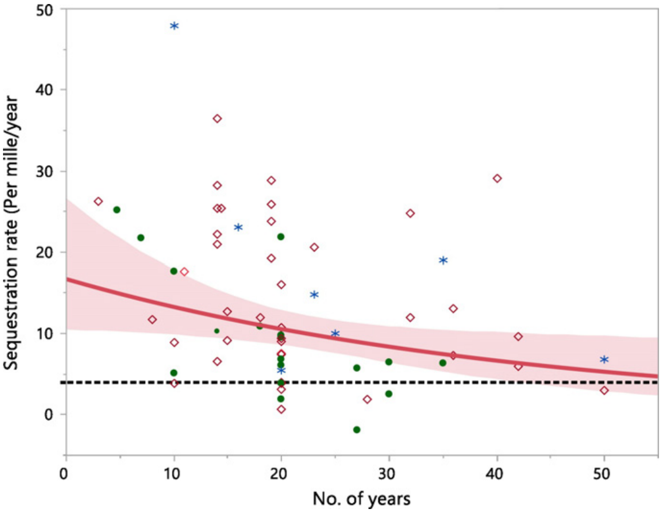


Fig. 15. Reported per mille sequestration rate as a function of number of years since management practices been implemented. Data are based on studies in different regions reported in Table 1. Red curve is a regression model fitted to the data with 95% confidence interval presented as shaded areas. Red diamonds refer to cropping land, green dots are grassland, and blue stars are forestry/plantation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

plantations can actually sequester soil carbon at the same rate as native forests (Khasanah et al., 2015). There is another argument that this sequestration is negated as the plantation is an outcome of deforestation with a carbon debt (Gibbs et al., 2008); nevertheless, looking in the future, avoiding further deforestation and well-established plantations should be able to sequester C.

Cropping management strategies that are based on exogenous C inputs (via addition of compost or manure, or biochar sourced elsewhere) also require additional energy, cost, and resources which may not be feasible. There has also been an interest in composting urban waste for use as soil amendment in urban agricultural areas for SOC sequestration and nutrient cycling. A study by Paetsch et al. (2016) showed that two years after treatments in a cropping area in France showed no SOC stock changes for municipal solid waste compost amended soils, however application of composts from organic waste and green waste and sewage sludge increased SOC stocks in a similar range as conventional farmyard manure. The increased C storage in the clay fractions of the soil amended with organic wastes and green waste and sewage sludge compost and farmyard manure may be improved by a better microbial efficiency leading to C sequestration as microbial compounds.

Powlson et al. (2011) argued that C sequestration resulting from organic amendments depends on the fate of the material. It can be just a transfer from one terrestrial C pool to another, and thus has no influence on mitigating climate change. In Canada and France, manure application is currently not considered as a climate change mitigation measure. All manure is already applied to soil and therefore no additional sequestration of SOC is expected compared to the default condition. Research in India by Pathak et al. (2011) argued that manure application in a farm, which otherwise will be used, recycled or discarded elsewhere, increased soil productivity, crop yield, and thus contributed to carbon sequestration. The application of straw or crop residues in soil which would otherwise be removed from the field or burnt constitutes C sequestration. Application of additional inorganic fertilizer which enhances crop growth, and thus additional C sequestration, needs to consider the additional energy and greenhouse gases associated with them. The SOC change maybe an avoided emission.

In situ management strategies (Smith et al., 2008), such as stubble retention, reduced tillage and crop rotation are possible options. Conservation methods, such as the use of nitrogen-fixing legumes, in addition to no-till practices increase carbon sequestration. In Australia, pastures and legumes rotated in a ley farming system were found to sequester C at a rate of 0.26 t C ha^{-1} $year^{-1}$ when no till and stubble retention were practiced (Chan et al., 2011). A 40-year study in a semiarid subtropical region in Australia showed that crop residue retention, with moderate rate of N fertilizer application under no-tillage provides an optimum management practice for crop yields and SOC management in the soil (Dalal et al., 2011). Nevertheless, a survey by Llewellyn and D'Emden (2009) for grain growers in Australia, found that the no-till practice has already been adopted by more than 70%, and in many areas it has reached near 90%. There is a challenge to find the next step innovation that can boost SOC.

Any increase in soil carbon, even only in the topsoil, should benefit cropping soil, which has lost half of its carbon since being used for cultivation in Australia and other parts of the world (Luo et al., 2010). Increasing SOC promotes soil structure, and leads to a more productive soil and increased crop yield (Stockmann et al., 2015).

3.3. Time

SOC is dynamic and can follow the so-called "transition curve" following clearance of natural vegetation for cropland (van Noordwijk et al., 2014). At the first stage there is a rapid decline of soil carbon due to clearing, this is followed by a critical phase of diminished soil fertility and finally by recovery once agricultural practices improve (Minasny et al., 2011) (Fig. 16). Sequestration rates are high during initial years when best management practices have been applied (Fig. 15) and decline as time progresses as soil has reached equilibrium. Thus, sequestration rates are most efficient following a restoration of degraded lands or a radical soil management. Topsoil can respond rapidly to soil management and build-up soil carbon.

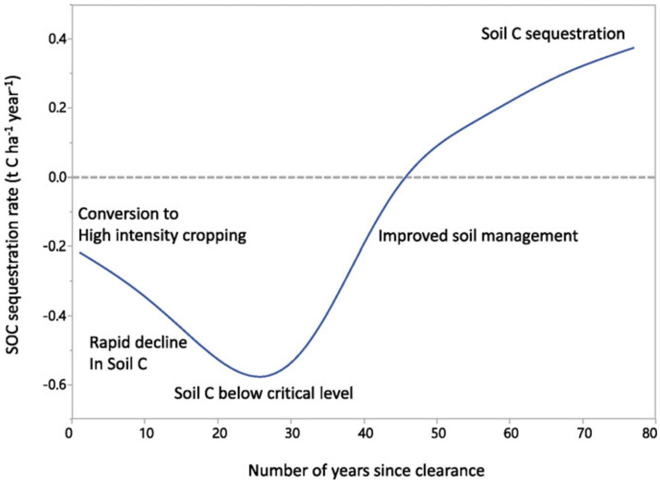


Fig. 16. SOC sequestration rate following conversion of native vegetation to high-intensity cropping, a degraded state, and a positive sequestration following improved soil management for a tropical system (based on Minasny et al., 2011).

Nevertheless, the permanence of the carbon is still being debated (Wheeler, 2014; He et al., 2016). Ideally, it is desired to convert input organic matter into passive pools with longer residence time. Chan et al. (2001) showed the presence of a relatively higher proportion (65%) of SOC in the labile pools and a smaller proportion in the passive pools in semiarid areas of Australia. Mid Infrared technology has been shown to be able to measure inert or stable C (Janik et al., 2007) or other physical fractions (Henaka Arachchi et al., 2016) which has potential for future SOC assessment.

3.4. Critical limit & Capacity

Some authors suggest that soil has a limited capacity to accumulate carbon (Loveland and Webb, 2003), and that SOC saturation depends on clay and silt content (Hassink, 1997, Six et al., 2002). Conversely, there is also a critical C concentration, below which a soil's function is reduced significantly. It was hypothesised that there is a critical limit and saturation level which depends on soil texture and climatic condition (Stockmann et al., 2015). For example, the reported critical limit of SOC concentration in tropical soil is 1.1% (Aune and Lal, 1997), however most cropping soils in tropical regions of India have SOC levels of 0.5% or lower. The SOC saturation level in India was calculated to be 4 times lower than the relationships proposed by Hassink (1997). The challenge is to work out these critical levels and C saturation levels so that we can estimate the soil carbon saturation deficit (the difference between the theoretical SOC saturation value and the current SOC content) to identify hot spots and realisable C sequestration potential.

3.5. Paucity of data

There will always be lack of data for verification. However there are countries with well-established soil information systems, detailed estimates of sequestration rate potential (e.g. USA) and an established monitoring system (e.g. France). However in most countries, sequestration rates are mostly based on long-term experiments and soil legacy data. Thus a global effort on monitoring soil carbon would be beneficial in obtaining the global soil conditions, SOC sequestration potential, and rate of changes. While this may be seen to be a huge task, progress in

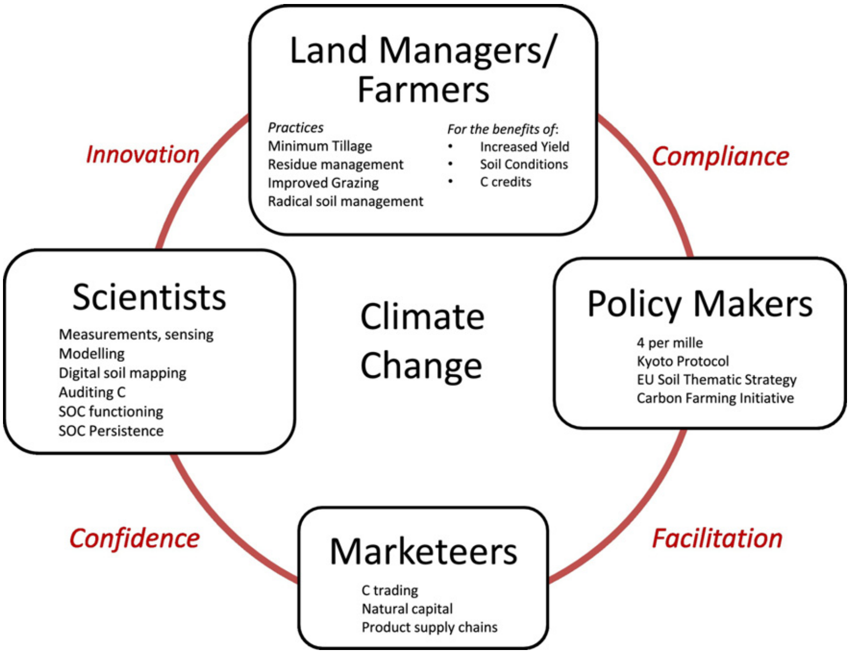


Fig. 17. Potential interactions between scientists, farmers, policy makers, and marketeers engaged in implementation of soil C 4 per mille initiative.

digital mapping and technology coupled with advanced sampling design allows us to gather enough information to be able to make statistically reliable estimates. For example, an optimal spatial sampling design by De Gruijter et al. (2016) could be applied globally using digital maps from the GlobalSoilMap project.

3.6. Implementation

Paustian et al. (2016) suggested ways to incentivise farmers to adopt management practices that can increase soil carbon via regulation and taxation, subsidies, supply-chain initiatives and carbon market. A means to facilitate and reward good management practices to sequester soil carbon is to treat it as a tradeable resource. A monetary value has been assigned to carbon, in all its states and forms, which allow for the trading and offsetting of carbon budgets. The development of carbon credit markets accessible to the private sector would allow for incentives such as government payments, tax credits, and/or emissions trading, which can aid in overcoming farmer reluctance to adopting management strategies that increase or maintain soil carbon (Rosenberg and Izaurralde, 2001).

There is still a debate on an efficient way of measuring SOC stock with appropriate statistical confidence for carbon sequestration verification. It is now established that we can monitor changes in soil carbon efficiently and effectively with sufficient statistical confidence. Rather than relying on process-based models with many assumptions, direct measurement can provide empirical evidence. De Gruijter et al. (2016) presented a method for soil carbon auditing. The method is based on stratified random sampling and design-based inference about the amount of sequestered carbon. Stratification, total sample size and sample sizes per stratum are mathematically optimized in conjunction. The criterion used is maximising the expected financial gain for the farmer, given a required level of certainty about the amount of sequestered carbon.

3.7. Disruptive technologies

We have had minimum tillage for 50 years, and if applied well it can achieve 4 per mille in many situations (Table 1). However we need a further scope to enhance SOC sequestration. Areas that have reached equilibrium, but not at saturation level, will not be able to increase their sequestration rate (Fig. 6). Because of small SOC stock gain per unit area when best management practices are applied, the 4 per mille can only offer short-term solutions. A simulation of climate change with increasing CO_2 up to the year 2100 in France by Meersmans et al. (2016) demonstrated that conversions of 100,000 to 200,000 km^2 of cropland into grassland or forest would be required to offset 10% of climate change induced loss of SOC. Only radical land use change coupled with enhanced C sequestration technology in productive agricultural land uses has the potential to mitigate climate change. Disruptive technologies such as radical soil management (McBratney et al., 2016) are possibilities.

Metting et al. (2001) discussed some of the new technologies for soil carbon sequestration more than 15 years ago which include (1) technology for soil, crop and forest management, (2) exploitation of underutilized land resources and existing biodiversity, (3) plant biotechnology, (4) microbial biotechnology, and (5) chemical technology. Precision technology now has been widely applied, enabling more efficient use of fertiliser and water. However, such technology has not really translated in enhanced soil C sequestration. Plant biotechnologies, include new plant species with greater net primary production and greater root mass and deeper exploration are still not widely available yet (Montes et al., 2011; Rasse et al., 2005; Rumpel and Kögel-Knabner, 2011). In addition, we cannot fully rely on inorganic fertilizers to build up plant biomass. Plants that are able to fix N with a greater water use efficiency are required (Sinclair and Horie, 1989).

Since no till shows accumulation of soil carbon only on topsoil, occasional cultivation to bury the organic matter may enhance C sequestration at depth. Through radical soil management, clay may be added to subsoil or bringing subsoil clay to the surface can rejuvenate soil. This is relevant in Australia, where weathered soil can be rejuvenated cost-effectively, and these soils can soak more carbon and lift productivity (McBratney et al., 2016). Hamilton et al. (2016) showed that a subtle soil disturbance to a depth of approximately 300 mm using a specially designed blade loosener, with controlled traffic and no-tillage can stimulate plant growth and stabilise a loosened and deepened root zone. Manipulation of soil microbial community dynamics may also enhance C sequestration (Bailey et al., 2002; McDaniel et al., 2014). Research is warranted to verify the practicality of these systems.

4. Conclusions

The 4 per mille is an ambitious aspiration, however, for the first time this initiative is setting a global goal to promote good soil management that can help mitigate climate change. Agricultural areas hold about 600 Gt of C in their top 1 m of soil. Increasing SOC stocks for all of these areas by 4 per mille (about 2.5 Gt C year^{-1}) can offset about 30% of global greenhouse gases emission. Paustian et al. (2016) calculated a GHG mitigation potential of 2.2 Gt C year^{-1} for soil management practices. As summarised by Lal (2016) it should be more about the concept than any specific numbers.

Examples showed that there is some scope globally to increase SOC. The challenge for cropping farmers is to find a new generation of practices that will further improve soil condition and deliver increased soil carbon. We need disruptive technologies that can help agricultural practices to soak up more carbon in the soil, create soil security to achieve food security and mitigate climate change. Such technologies should also avoid offsetting effects for different greenhouse gases (Paustian et al., 2016). In addition, the initiative is an opportunity to implement a sound and credible soil carbon auditing protocol for monitoring, reporting, and verifying SOC sequestration which can be fit into national GHG inventory procedures (Chambers et al., 2016).

As a strategy for climate change mitigation, SOC sequestration should be implemented immediately. It buys time over the next ten years whilst other effective sequestration and low carbon technologies will become viable. Progress in 4 per mille requires collaboration and communication between scientists, farmers, policy makers, and marketeers (Fig. 17). Farmers and land managers primarily apply management practices to improve their soil's condition and, in doing so can also contribute to the sequestering of C and mitigating climate change. Scientists provide **innovation** that can result in enhanced C sequestration, monitor the impact of climate change on SOC, and SOC functioning. Scientists also develop new technologies in measurement, mapping, and auditing to verify SOC sequestration, which is expected by the market to provide **confidence** in investment. Farmers' SOC sequestration effort provides **compliance** to the policy makers. This has to be integrated with institutional regulations and policies that **facilitate** market-based approaches, such as C trading. Soil C 4 per mille can make soils a sustainable resource, not a renewable resource.

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