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Review

A paradigm shift to CO_2 sequestration to manage global warming – With the emphasis on developing countries

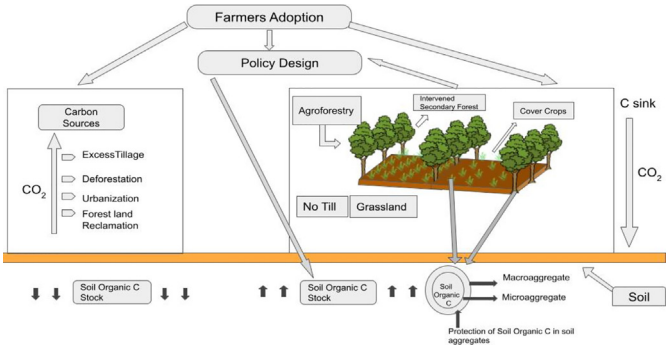
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HIGHLIGHTS

- Agricultural management practices for C sequestration are time dependent.
- Substantial amount of CO_2 could be mitigated by agroforestry systems (AFS).
- Annual 725 $Euro_{eq}$ C Credit could be achieved through AFS in EU.
- Grasses and Cereals can capture 76% C through shoots.
- More policies and research required for C sequestration in animal-plant-soil system.

GRAPHICAL ABSTRACT



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ABSTRACT

Global land use changes that tend to satisfy the food needs of augmenting population is provoking agricultural soils to act as a carbon (C) source rather than sink. Agricultural management practices are crucial to offset the anthropogenic C emission; hence, Carbon sequestration (CS) in agriculture is a viable option for reversing this cycle, but it is based on hypotheses that must be questioned in order to contribute to the development of new agricultural techniques. This review summarizes a global perspective focusing on 5 developing countries (DC) (Bangladesh, Brazil, Argentina, Nigeria and Mexico) because of their importance on global C budget and on the agricultural sector as well as the impact produced by several global practices such as tillage, agroforestry systems, silvopasture, 4p1000 on CO_2 sequestration. We also discussed about global policies regarding CS and tools available to measure CS. We found that among all practices agroforestry deemed to be the most promising approach and conversion from pasture to agroforestry will be favorable to both farmers and in changing climate, (e.g., agroforestry systems can generate 725 $Euro_{eq}$ C credit in EU) while some strategies (e.g. no-tillage) supposed to be less promising and over-hyped. In terms of conservative tillage (no-, reduced-, and minimal tillage systems), global and DC's land use increased. However, the impact of no-tillage is ambiguous since the beneficial impact is only limited to top soil (0–10 cm) as opposed to conventional mechanisms. Grasses, cereals and cover crops have higher potential of CS in their soils. While the 4p1000 initiative appears to be successful in certain

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areas, further research is needed to validate this possible mode of CS. Furthermore, for effective policy design and implementation to obtain more SOC stock, we strongly emphasize to include farmers globally as they are the one and only sustainable driver, hence, government and associated authorities should take initiatives (e.g., stimulus incentives, C credits) to form C market and promote C plantings. Otherwise, policy failure may occur. Moreover, to determine the true effect of these activities or regulations on CS, we must concurrently analyze SOC stock adjustments using models or direct measurements. Above all, SOC is the founding block of sustainable agriculture and inextricably linked with food security. Climate-smart managing of agriculture is very crucial for a massive SOC stock globally especially in DC's.

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Contents

1. Introduction . . . 2
2. Interlinkages of global warming, CO_2 sequestration and agricultural practices . . . 3
3. Environmental and economic context for agricultural practices and carbon sequestration in developing countries . . . 4
3.1. Analysis of tillage systems for developing countries . . . 4
3.2. Agroforesty, land use patterns, silvopasture, and pasture management . . . 5
3.3. Crop rotation, cover crops, and crop types . . . 6
3.4. 4 per 1000 initiative (4p1000) . . . 6
3.5. Conservation agriculture (CA) . . . 6
4. Global agricultural policies to foster carbon sequestration: an overview . . . 7
5. Methods available for measuring carbon sequestration . . . 8
5.1. Direct measurements . . . 8
5.2. Remote sensing . . . 9
5.3. Model-based estimation . . . 9
6. Concluding remarks and recommendations . . . 9
Declaration of competing interest . . . 10
Acknowledgements . . . 10
Appendix A . . . 10
References . . . 10

1. Introduction

Greenhouse gases (GHGs) particularly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) play a direct role in Climate Change (CC) but, CO_2 is prevalent among these with the highest contribution (65%) to global emissions (IPCC, 2014; Rogelj et al., 2018; Rodas-Zuluaga et al., 2021). CO_2 is considered as a parameter to calculate the Global Warming Potential (GWP) for the other gases (EPA, 2021). Global atmospheric CO_2 concentration has increased from 280 ppm to 409.09 ppm between the 18th century (pre-Industrial Era) and 2019, with an estimated annual growth rate of 3.40 ppm $year^{-1}$ as of 2018 (NOAA, 2020). This increase in atmospheric CO_2 concentration has raised concerns given its association with global mean temperature and CC (Olivier and Peters, 2020; Stern, 2007). The emerging trend in atmospheric CO_2 concentration points to the first instance of the human-induced increase in GHGs emissions (Paustian et al., 2016). Such concerns are highlighted for developing countries (DC) such as Brazil, Nigeria, Mexico, Bangladesh and Argentina which base their economies in agricultural commodities export, since agriculture is deeply affected by CC and these exports represent 12.3% of the global agricultural commodities (Data, 2019). Under this context, Carbon Sequestration (CS) in agriculture sector is a valuable alternative to reverse such trend, but lies over assumptions that must be challenged in order to lead to develop novel agricultural techniques. Among all anthropogenic sources of GHGs emissions, agriculture and related primary activities play a pivotal role, yet, these practices are crucial for CS. Agricultural GHGs increased two-folds during the period 1961–2017 (Tubiello et al., 2014), and are projected to increase by about 7% for the period 2017–2030, bringing the net agricultural GHGs emission to 12.3 Pg (Peta gram) of CO_{2eq} (FAOSTAT, 2018). This projection is a significant hint to cope up with GHGs emissions, since Agriculture, Forestry and Other Land Use (AFOLU) sector contributes 24% to global emission (IPCC, 2014). To downscale both the projection and the share of agricultural GHGs emissions, adopting best practices is a major task for agricultural systems. Farming intensification has stressed agricultural soils to act as enhanced emitter of GHGs due to the soil disturbances by practices such as tillage, pastoralism, bush burning, deforestation, uncontrolled/continuous grazing, continuous cropping, and intensive confined animal feeding operation; (Gerber et al., 2013; Bellarby et al., 2008).

As can be seen in Fig. 1, agricultural practices are a substantial source of atmospheric CO_2 depleting soil organic carbon (SOC) stock. Even though there is a conceptualization that SOC stock must be restored and augmented through roots and biomass decomposition resulting of either cover crops or no till or grasslands whereas cattle manure management, CS into plant trunks is also a valid alternative for those systems leading to circular economy such as agroforestry or silvopastoral systems (Terrer et al., 2021) (Fig. 1). Also, sequestering in either soil or plant biomass is a trade-off that needs to be addressed. To quench this thirst of knowledge, taking advantage of previously published long-term and short- term field researches, meta-analyses published in peer-reviewed journals we searched literatures in Google scholar search engine introducing the term “carbon sequestration”, “agriculture”, “agricultural management practices”, “C sequestering policies” and so on to build a database of 200 literatures.

Soil organic carbon stock depletion can be observed worldwide but it is especially important for soil health in the 5 DC mentioned above where the top 100 cm soil layer concentrates 5 to 10 kg C m^{-2} as a result of agricultural activities promoting CO_2 loss (Fig. 2). Therefore, there is a need to improve agricultural practices to offset soil CO_2 emissions through both crop and cattle management practices. This premise becomes relevant under the framework of 2030 Agenda for Sustainable Development Goals (SDGs) as an important factor to be accomplished (United Nations, 2020). Even though efforts to achieve this goal have stirred several research studies with many recommendations, most of them are costly and not workable for low-income countries of Africa,

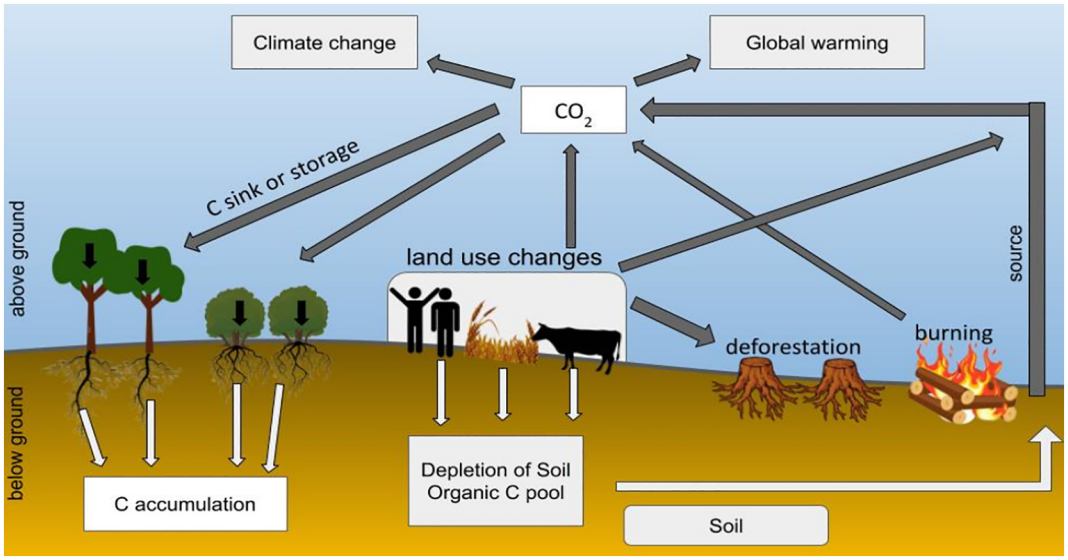


Fig. 1. Conceptual schematic representation of different pathways of CO_2 releases to the environment. Land use changes (deforestation, burning, etc.) alters the SOC stock and emit CO_2 while vegetations act as a potential C sink and reduce anthropogenic C emissions.

Asia and South America. Under this context, economically feasible practices leading to CS have been widely advocated as a potential tool to offset CO_2 emissions (Smith et al., 2008; Lal et al., 2018; Smith et al., 2020; Mathew et al., 2017; Keel et al., 2019) derived from the practices performed in croplands, forests, orchards, pastures and rangelands. Regarding this aspect, SOC stock expansion is central to the adjustments of potential damages of CC i.e., abatement of GHGs and anthropogenic CO_2 discharges along with improved soil health. Slight changes in SOC can trigger substantial variations in atmospheric CO_2 concentration (Wiesmeier et al., 2020; Stockmann et al., 2013).

Additionally, empirical findings (Papini et al., 2011; Saha and Kukal, 2015; Gupta and Sharma, 2014; Gupta and Sharma, 2013; Zhong et al., 2019; Martí-Roura et al., 2019) demonstrated that C can be sequestered through a combination of several practices under extant policies. This, importantly, raises questions on the adequacy of the current agricultural practices to sequester enough CO_2 and upturn the negative effects of CC occasioned by enormous agricultural GHGs emissions. The objective of this review is to collate, synthesize and analyze the current state of agricultural practices leading to CS, contextualizing the feasibility of improving agricultural practices globally emphasizing on five Developing Countries. Here, we also focus on global policies aimed to foster CS and methods employed in measuring CS. This study is structured as follows. Section 2 provides an inter-linkage of global warming, CO_2 sequestration and agricultural practices; Section 3 gives an in-depth overview of current practices being practiced globally for CS; Section 4 shows a concise overview of global policies; Section 5 depicts detailed available methods for measuring CS; Section 6 contains conclusions and recommendations.

2. Interlinkages of global warming, CO_2 sequestration and agricultural practices

The dramatic rise in GHGs emissions and concentrations in the atmosphere has increased the earth's surface mean temperature because of radiation balance changes (greenhouse effect): the more GHGs concentration in the atmosphere, the less long wave radiation escaping to outer space; resulting in global warming (Kweku et al., 2018) and then CC. Substantial environmental havocs emerged including melting

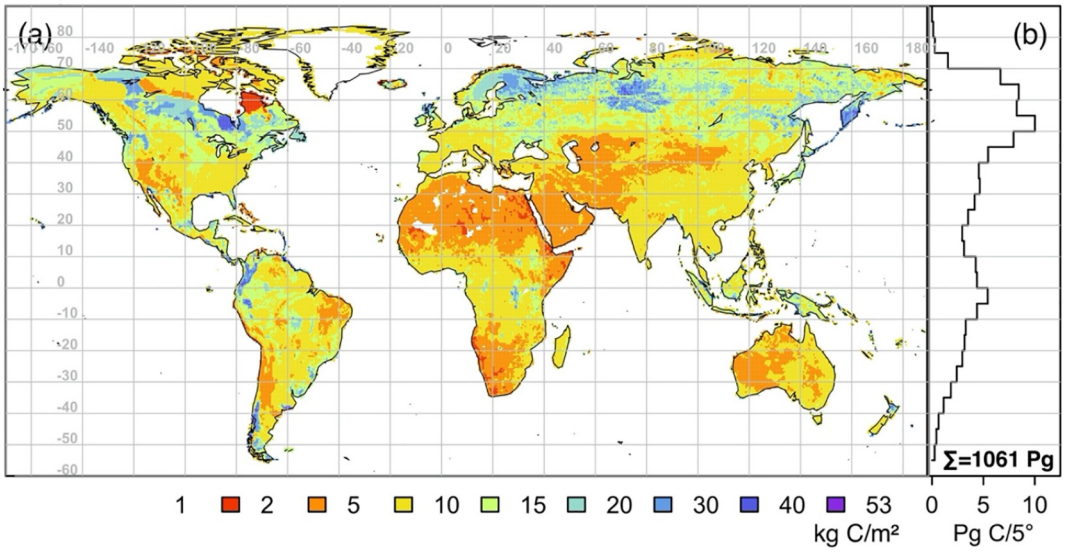


Fig. 2. Global SOC stock (a) and mass (b, per 5° latitude) in the top 100 cm of terrestrial soil (Köchy et al., 2015).

of mountain glaciers, decreased snow cover in the Northern Hemisphere, reduced precipitation in the tropics, increased sea level, rise in ocean acidification, thinning and reduced Arctic ice and area, and loss of plants and animals' biodiversity (IPCC, 2013; Wanner et al., 2008; Tett et al., 2007). Also, recent catastrophic events e.g., heat waves, tropical cyclones, floods, and drought provided interesting evidence of global warming and CC (Kweku et al., 2018). These events CC-related have been dramatic for the agricultural sector of DC. For example, during 2018, Argentina's agricultural sector lost 4.6 billion USD due to a severe drought (Bolsa de Comercio de Rosario, 2018). Furthermore, the locust outbreak in Southwest Asia and Africa during 2020 produced significant economic losses, with regions deeply affected such as the Northwest of Nigeria (FAO, 2020a, 2020b). Thus, reducing GHGs emissions is a critical aspect to cope with CC. Pooled agricultural emissions of Brazil, Nigeria, Mexico, Bangladesh and Argentina represent 14.9% of global agricultural emissions (FAOSTAT, 2018), so those agricultural practices reducing emissions, enhancing SOC stock, offsetting SOC respiration and improving livestock diets are rather desirable for emissions mitigation in these DC. The common thread among such practices is CS, which has been defined as the process of capturing and storing atmospheric CO_2 in soil, vegetation, ocean, and geologic basalt, for a certain period (Lal, 2004). The process ensures fixation of atmospheric CO_2 into the various plant parts via photosynthesis and later incorporates the C into the soil via the activities of soil microorganisms (Mandal et al., 2020; Kishwan et al., 2009; Kemmitt et al., 2008).

Carbon sequestration occurs following many age-old agricultural practices, including mixed crop-livestock farming system, conservation agriculture, organic agriculture, and agroforestry among others (Hui et al., 2015; Zuidema et al., 2013; FAO, 2011). Studies showed that CS through some agricultural practices can offset GHGs emission in terms of $CO_{2\ eq}$ (metric used to compare emissions from several GHGs on the basis of their global warming potential).For instance, improved grazing management practices in grasslands was estimated to sequester 0.41 Pg CO_2 over a 20-year period (Gerber et al., 2013), while Ussiri and Lal (2009) observed 48% and 52% less global warming potential and net CO_2 emission for no-till than moldboard till and chisel till, respectively. This corroborates the findings of de Vries et al. (2009) that CS rates respond to reduced emission/concentration of GHGs. The CS, therefore, serves as a regulator, controlling the harmful effects of increased emission/concentration of GHGs on the environment through changing climate (Zhu, 2010). In spite of CS advantages, CS-related practices are not widespread yet and CO_2 emissions produced by agricultural activities are far to be offset with a minimum level of adoption (Jantke et al., 2020). The global GHGs emission since the beginning of agricultural practices particularly, forest clearing and burning was estimated at 133 Pg CO_{2e} and has more than doubled (379 Pg CO_{2e}) in the 20th century (Sparrevik and Utstøl, 2020; Nayeb et al., 2019; UNEP, 2019; Zheng et al., 2019; Houghton and Nassikas, 2017; Lal, 2004).

Agricultural practices such as land cultivation/tillage for forage crops production contribute around 8 to 16 Pg CO_{2eq} and also triggered extensive (50% to 70%) loss of soil C stock (Sanderman et al., 2017; Le Quéré et al., 2016; Teague et al., 2016; Pan et al., 2011; Zomer et al., 2013). Also, GHGs emissions from production, storage, and distribution of agricultural inputs and their application with mechanized equipment have significant impacts. For instance, production, storage, and application of manures and synthetic fertilizers accounted for 1.8 Pg CO_{2eq} and 0.6 Pg CO_{2eq} respectively, while on-farm energy use contributed 1.0 Pg CO_{2eq} (Ahmed et al., 2020; IPCC, 2014). Deforestation and forest degradation due to land-use change over the period 1990 to 2010 produced about 1.4 Pg C yr^{-1} (IPCC, 2013; Houghton, 2012). Emissions from cattle (beef and dairy cows) production alone was estimated at 8.3 Pg CO_{2eq} and surpassed the total GHGs emission of any country aside from China (Ahmed et al., 2020). Overall, GHGs emissions from AFOLU activities accounted for about 13% CO_2, 45% CH_4, and 82% N_2O of global human activities during 2007–2016, representing 27% (19.9 Pg CO_2) of total anthropogenic emissions of GHGs (Ahmed et al., 2020). Cusack et al. (2021) compiled 292 local comparisons of "improved" versus "conventional" beef production systems across global regions, assessing net GHGs emission data from Life Cycle Assessment (LCA) studies. They found that net beef GHGs emissions could be reduced substantially via management changes. This study mentioned that overall a 46% reduction in net GHGs emissions per unit of beef was achieved at sites using CS management strategies on grazed lands, and an 8% reduction in net GHGs using growth efficiency strategies (this reduction depending on the baselines); the net-zero emissions were only achieved in 2% of the studies. Thus, a combination of CS and efficiency improvements could be promisors. Then, given the magnitude of these contributions to global agricultural emissions, feasibility analyses about CS practices implementation are needed, particularly for DCs being vulnerable to CC but at same time depending on agricultural exports for global trade.

3. Environmental and economic context for agricultural practices and carbon sequestration in developing countries

Pooled area devoted to agricultural land of Brazil, Nigeria, Mexico, Bangladesh and Argentina accounts for 571 M ha, contributing with 11.2% to the global agricultural area (FAO, 2019; The World Bank Data, 2019). Then, a contextual and prospective analysis for these DC may lead to a better comprehension about what CS-linked practice is better to encourage and recommend depending on environmental and economic context at global and local level. Regarding environmental indexes, the global SOC pool is 1550 Pg, which is about 3.3 times higher than the atmospheric C content and 4.5 folds higher than the C in vegetations (Lal, 2004). The SOC is a universal indicator of soil quality, important for ecological, physical, and biological functions,; fluctuations in SOC levels can occur due to land-use changes (Stolbovoy et al., 2007) and can be a causal agent of soil fertility depletions, soil erosions, and emission of GHGs. Best management practices include conservation agriculture (CA), sustainable intensification (SI), integration of crops with trees (agroforestry) and livestock (mixed farming), and restoration of soil health through CS (Lal, 2019). Agricultural practices can act as both emitters (sources) and C capturing agents (sinks) (Aertsens et al., 2013, Moreira et al., 2020; Paustian et al., 2016). C sequestering management practices are largely climate-dependent (Conant et al., 2001) in both temperate and tropical regions (Ogle et al., 2005). Soil C content and concentration along with CS rate significantly increase with improved practices, e.g., improved fertilization, improved grazing management, water management, etc., but it is highly time-dependent. For instance, the highest CS rate was observed in the first 40 years on the top 10 cm of soil (Conant et al., 2001).

In economic terms, Gross Domestic Products (GDP) per capita from Brazil, Argentina and Mexico are close or above the world GDP per capita (15,299, 23,040 and 20,944 vs. 17,811 USD yr^{-1}, respectively) while those of Nigeria and Bangladesh are below this average (5362 and 4964 USD yr^{-1}), whence the building of resilience through CS will benefit the more to the latter group of countries (World Bank, 2020). Also, it must be noted that agriculture-based economies have a certain degree of specialization for exports: for example, Brazil and Argentina are specialized in export grains and beef meat, Mexico in beer and horticulture species, while Nigeria and Bangladesh main commodities are specialized in cocoa beans and jute respectively (FAO, 2019). However, since the point of view of the domestic market, the five countries are similar producing sugarcane, maize, soybeans, wheat, rice, cassava, yams, milk and meat (Table A1). Therefore, alternative food production systems relying on the concept of CS may allow farmers and stakeholders to cope with CC, diminish economic vulnerability resulting from specialization and at the same time improve food security.

3.1. Analysis of tillage systems for developing countries

Tillage is the land preparation technique, i.e. mechanical manipulation of the soils for preparing seedbeds for planting crops. Several tillage

practices viz. No-tillage (NT), Reduced Tillage (RT), Conservative Tillage (CT) are advocated globally for CS in cultivated soils. Global land under these practices went from 111 M ha in 2009 (Derpsch et al., 2010) to 160 M ha in 2013 (Kassam et al., 2015). The reason behind adopting NT, RT and CT system is that, acute tillage forces SOC to be depleted easily (Acir et al., 2020). Dimassi et al. (2014) concluded tillage doesn't have massive impacts on SOC stock after certain periods from top to deeper soil depth, but agreed NT can improve SOC stock in top 10 cm soil (Angers and Eriksen-Hamel, 2008; Luo et al., 2010; Acir et al., 2020), yet follow an inverted "U" shaped curve. In terms of whole soil profile Impact, longstanding results revealed NT is inferior to CT (Blanco-Canqui and Lal, 2009). Soils under NT practice exhibit declined SOC in deeper soil depth, which entails insignificant variances exist between CT and NT (Corbeels et al., 2020).

Argentina and Brazil account for ca. 70 M ha with crops under those systems (Rainaudo, 2019; IBGE, 2017), which is the main reason behind the share of crop residue on emissions, with 0.01 Pg CO_{2eq} for Argentinean agriculture, emitting mostly N_2O (MCTI, 2020). Regarding the Mexican case, a study showed partial to low level of adoption of RT or CT for corn crops due mainly to lack of information and lack of equipment (Van den Broeck et al., 2013). In Bangladesh, the adoption of RT, NT and CT is increasing, covering up to 26,000 ha in 2012 (Hossain et al., 2015). Also, Nigerian smallholders are increasingly adopting this farming technique (Olawuyi, 2019).

Again, contrasting results are also available. Adoption of NT in agricultural systems improved the SOC, N fractions and soil microbial activity (Rigon et al., 2020; Pu et al., 2019). NT practices under specific pedo-climatic conditions can expand SOC stock, decrease the net releases of GHGs but, owing to contradictory results, implementing NT has solved SOC conservation (Ogle et al., 2019). NT practices are futile in terms of SOC maintenance and steady aggregate development compared to CT in rainfed Mediterranean olive orchards. NT also promotes less N_2O emission when compared to the CT (plowing) in Brazilian soils (de Figueiredo et al., 2018).

Less soil disturbance is the actual mechanism of NT which promotes ultimately greater aggregation of soil particles when compared to CT with soil plowing. CT eventually yields more exposure of SOM to the microorganisms, greater mineralization of SOC, and CO_2 emission (Galdos et al., 2019; Marafon et al., 2020).

In arid regions where fine and medium-textured soils are common, Deep Tillage (DT) can induce CS significantly compared to CT. Although, the whole soil profile is not influenced and surface SOC stock seems to be low, but SOC stock increases significantly in subsurface soil (20–50 cm depth), spatial fluctuations within sites and appropriate agronomic practices while DT will be prescribed for CS (Feng et al., 2020). Finally, results are controversial for these practices in terms of SOC stock conservation and GHGs emissions, but with adequate management of residues, fertilizers and other agronomic variables may be an alternative to improve soil health and conserve SOC for drier and sandy environments (Abdalla et al., 2016), an alternative particularly interesting for countries with lower income such as Bangladesh or Nigeria (Table 1).

Table 1
Effect of different tillage practices equipped with different parameters on SOC sequestration at the topsoil of the Mediterranean region (modified from Acir et al., 2020).

Tillage practices	C sequestration (Mg C ha^{-1})
CT with residue retention	10.922.8 ± 0.380
CT with zero residue	9.946 ± 0.251
RT with heavy tandem disc harrow	15.007 ± 0.308
RT with rotary tiller	17.190 ± 0.307
NT	19.121 ± 0.518
ST	16.696 ± 0.406

CT = Conventional Tillage, RT = Reduced Tillage, NT = No Tillage, ST = Strategic Tillage.

3.2. Agroforesty, land use patterns, silvopasture, and pasture management

Clearing of native vegetation by changing land-use patterns to meet up with the food demand for the augmenting population has become an obvious phenomenon all over the world. SOC stock in soils is depleting while influencing largely the soil microflora and fauna. Not only the soil can substantially sequester C, but also tree biomass, since forests can increase their biomass in ca. 23% with elevated CO_2 while grasslands only can increase biomass in ca. 6% (Terrer et al., 2021). In such sense agroforestry systems (AFS) are a valid alternative to sequester carbon for DC. Although information is scarce, the global area under agroforestry is estimated to be around 1000 M ha (Kumar et al., 2014).

Several studies across the world have agreed and acknowledged the inherent CS potential (acting as C sink) of agroforestry (Albrecht and Kandji, 2003; Ramachandran Nair et al., 2010; Aertsens et al., 2013; Dold et al., 2019; Cárdenas et al., 2019; Muchane et al., 2020). However, despite of the latter statement, tree cover has been ignored or neglected in most global and regional calculations (Zomer et al., 2016). Trends on total biomass C, were different among DC between 2000 and 2010, with Brazil and Bangladesh having increases of 13.8% and 19.8%, and Argentina and Nigeria having decreases of −20 and −5.8%, respectively (Zomer et al., 2016). The fires in the Brazilian Amazonia during 2019 have affected that trend since it is estimated 0.63% of the C sequestered in biomass was lost (Cardil et al., 2020).

AFS tend to improve SOC composition compared to mono-cropping and have the potential to influence soil macroaggregates formation through above and below-ground processes (Rodríguez et al., 2021; Muchane et al., 2020). However, with grasslands soil CS is higher than that of trees, while with trees biomass CS is higher than that of grasslands (Terrer et al., 2021), having AFS a complementary effect on CS. Again, stable aggregate (macro & micro) formation and preservation of SOC within aggregates is a noteworthy mode for SOC sequestration. Rhizosphere soil contains more SOC than non-rhizosphere soil, showing the roots effectivity in fixing C in soil (Li et al., 2020). Macroaggregates are eminent SOC binders; microaggregates are sculptured within them, SOC remains steady in the smaller pore because of their unwavering captivating ability (Conrad et al., 2018). A study by Rodríguez et al. (2021) found that root macroaggregates can store 14.1 g C kg^{-1} in Colombian deforested Amazonia. Pasture and arable land management through AFS can offset approximately 0.02 Pg $CO_{2\text{-eq}}ha^{-1}$ yr^{-1} while ensuring a net C credit of 725 Euro ha^{-1} over a 19-year timeframe in Europe (Aertsens et al., 2013). Different AFS stored an average of 91.3 ± 4.1 Mg C ha^{-1} in entisols and inceptisols (Rodríguez et al., 2021).

Additionally, trees can contribute to C capturing process both by their above-below ground biomasses and by woody contents too. Quantifying CS through above and below ground biomasses has gained reliability (Narayana et al., 2020). A 17-year comparative study on silvopastoral systems in the temperate regions of the USA suggested that plantation of Northern Red Oak (*Quercus rubra*) and Pecan (*Carya illinoinensis*) can contribute to the overall CS via their woody C content 0.75 Mg ha^{-1} and 0.20 Mg ha^{-1}, respectively (Dold et al., 2019). Woody plantation is sustainable in C capturing. Presence of the tree in silvopastoral systems can reduce animal thermal stress, increasing daily weight gain and reducing the slaughter time, enteric methane emissions, and simultaneously, the emission intensity of the system (Chará et al., 2017; Domiciano et al., 2020; Herrero et al., 2016).

AFS significantly rely on land usage patterns in terms of C releasing or keeping potential (Cárdenas et al., 2019). Transformation of natural biomes to croplands pays off with a greater loss of C in tropics (West et al., 2010), and transition in land usage and cultivation processes influence C stock (Bennett et al., 2009). Data revealed that every ton of annual crop production requires three folds of C emission in terms of newly cleared vegetations in the tropics. Again, approximately 91.5 Mg C ha^{-1} is lost from tropical soils with a poor yield of approximately 2.8 Mg ha^{-1} yr^{-1} compared to temperate zones (West et al., 2010).

Practice dependent, but a potential C sink is grasslands (Conant et al., 2001; Bennett et al., 2009; McSherry and Ritchie, 2013; Mahanta et al., 2019), however, some results may vary depending on the regions (Viglizzo et al., 2020; Peri et al., 2017; Villarino et al., 2020; Alvarez et al., 2021). They are the major CO_2 removal agent as they remove around 20% of the emissions derived from the clearing of vegetation and land conversion (Follett and Reed, 2010). Globally, grasslands occupy around 26% of total lands with an assessed storage of 343 Pg C, and they subsidize to one-fourth CS through soils (Mahanta et al., 2019). Improved grazing, farming of advanced fodder species etc. can help to enhance the CS potential of grasslands (Mahanta et al., 2019). Grass species, e.g., C4 compared to C3 can accumulate more SOC stock in terms of grazing. However, grazing has a more positive effect at the deeper soil depth (>40 cm), and the grazing intensity, soil texture, and climate are interlinked with each other. For example, a dry climate (Central Asia) with strong grazing in sandy soils can provoke the grasslands to act as a C source instead of a C sink but grazing in clay soils having the same climatic conditions is sustainable (McSherry and Ritchie, 2013). Legume-based grass pastures can influence CS (e.g., Leucaena), and they can exhibit the biological nitrogen fixation, reducing the use of chemical fertilizers (Conrad et al., 2018). Properly managed pastures have great potential to preserve the aggregate structure, and because of the extensive root system, soil cover with grass residues increases labile C, and consequently the soil C stock (Gmach et al., 2018).

The rotation between crop and pastures optimizes the biological cycling of nutrients, promoting greater yield efficiency, greater supply of organic matter, and better soil fertility conditions in the long term (Carvalho et al., 2014; Costa et al., 2018). Integrated crop-livestock-forestry systems (ICLF) aim to increase agricultural productivity by aggregating different agricultural, livestock, and forestry production, benefiting all the components (Balbino et al., 2011; De Moraes et al., 2014). The ICLF system has the potential to reduce GHGs emissions, recovery of degraded areas and, reduce the pressure to open new areas and deforestation (Alves et al., 2017; Cardoso et al., 2016). Unlike conventional agriculture, the management carried out in the AFS and ICLF promote enhancements in soil quality, by i) crops diversification ii) permanent vegetation cover, and iii) the reduction of soil erosion (De Moraes et al., 2014; Salton et al., 2014). These administrations can promote the increase of the SOC, and they can offset N_2O and CH_4 emissions from soils considerably along with the enteric fermentation of the animals (Conceição et al., 2017; Ribeiro et al., 2019). The CO_2-eq removal potentiality of agricultural practices are listed in Table 2.

3.3. Crop rotation, cover crops, and crop types

Losses of C along with deteriorated crop produce is a common scenario in different cropping systems. For example, in Argentina, a typical crop sequence including wheat, soybeans and corn can emit 0.7 to 2.5 Mg $CO_{2\ eq}$ ha^{-1} yr^{-1}, with rotations having more crop diversification emitting less carbon (Taboada and Peralta., 2020). Crop diversification can balance the losses as it substantially influences soil biodiversity along with SOC stock expansion e.g., crop rotation with cover crops and one/more crops instead of monoculture can contribute to the total soil C by 8.5% and 3.6%, respectively (McDaniel et al., 2014; Poeplau & Don,2015). About 8% of outright agricultural GHGs releases could be altered annually by cover crop cultivations while apparent 0.09–0.15 Pg SOC Yr^{-1} may be sequestered globally until C saturation occurs (Poeplau and Don, 2015). C saturation can significantly decline the SOC stock augmentation (Wang et al., 2021). McDaniel et al. (2014) predicted under present climatic decorations an annual increase of SOC of 119.2 ± 18.7 Mg C when there will be a rotation with cover crops, but, absence of cover crops (Presence of other crops) will lead to yearly 7.8 ± 25.6 Mg C deposition. The rotation of crops and grasses in the same area is strategic to increase the SOC stocks, and they get benefitted mutually, hence, the integrated crop-livestock systems (ICL) emerge as a workable alternative toward reaching a sustainable agricultural production in tropical climate regions (Carvalho et al., 2010) where C loss is much because of climatic set-up.

Different crop species have significant inter linkages with SOC, contribute to increased stock through shoots and roots. Mathew et al. (2017) estimated C content in above ground biomasses in natural grasses, cereals, fibers, legumes, oil crops, summer maize, winter wheat, and rice as 19.80 ± 1.16, 9.44 ± 0.45, 7.90 ± 1.00, 3.29 ± 0.63, 3.05 ± 1.16, 6.3 ± 0.34, 2.2 ± 0.35, 9.5 ± 0 Mg ha^{-1} yr^{-1}, respectively, which shows the greater ability of these crops to captivate atmospheric C in their shoots. However, grasses are found to be storing three folds more C in their roots compared to maize. Thus, the ultimate mechanism is: atmospheric C capture in shoots > translocation of C in roots > Soils > SOC stock increase > CS.

3.4. 4 per 1000 initiative (4p1000)

The 4p1000 initiative, adopted at COP 21 under the Lima-Paris Action Plan (LPAP) frame focuses on the restitution of the human-induced CO_2 releases by augmenting global SOC stock of the upper 0–40 cm soil at a 4% rate yearly (Wiesmeier et al., 2020; Soussana et al., 2019). 4p1000 aim can be achievable in continental, humid continental and humid subtropical climate under CA practices (Valkama et al., 2020); but highly region-dependent, i.e., projection is valid for studied regions only (Powlson et al., 2016). The Initiative promotes an innovative model for helping to mitigate CC, through an increase in SOC and contributing to CC adaptation and food security, and can contribute to SDG 15.3, by combating desertification and restoring degraded lands (Rumpel et al., 2020).

A feasibility study of 4p1000 on the arable lands and grassland soils at Bavaria, Southeast Germany exposed that management practices (cover cropping, agroforestry, improved crop rotation, organic farming, and conversion of cropland to grassland) for achieving the 4p1000 goal could result around annual 1% increase in the present SOC stock, indicating the target is not achievable although, 1.5% of total GHGs emissions can be moderated per year which represents the significant CC adaptation (Wiesmeier et al., 2020). It has been demonstrated that improvements in grazing management, along with levels of fertilization, sowing of legumes, addition of improved grass species, irrigation, and conversion from crops benefit SOC stock, with rates ranging from 0.105 to >1 Mg C·ha^{-1}·yr^{-1} (Conant et al., 2017). There are enormous potential and challenges in increasing SOC stocks in African and South American smallholder agriculture by the 4p1000 initiative and the South-South Cooperation (SSC) (Corbeels et al., 2019; Lal, 2019). The low SOC levels in Sub-Saharan Africa are associated with the limited resources of smallholder farmers, as CC mitigation is not a priority for them. However, the 4p1000 initiative should be promoted for positive impacts on crop productivity and for farmers' profitability (Corbeels et al., 2019).

3.5. Conservation agriculture (CA)

Given the current status of tillage practices for DC above mentioned (Sections 3.1 and 3.3), it is worthy to mention CA contribution to CS. Minimum tillage, crop remainder interception, and crop species

Table 2
CO_2-eq removal potentiality of different practices along with calculated C credits over 19 years' timeframe (modified from Aertsens et al., 2013).

Measures	CO_2-eq removal potential (Mg ha^{-1} yr^{-1})	Mean projected value (C credits) from 2012 to 2030 (Euro/ha)
Agroforestry on arable land	10.065	725
Pasture renovation by agroforestry	10.065	725
Hedge rows	0.366	27
Cover crops	0.586	43
Low/no tillage	0.366	27
All	21.448	1547

variations are the full sets of CA (Powlson et al., 2016; FAO, 2017; Gonzalez-Sanchez et al., 2019; Friedrich et al., 2017), also assumed as a mitigator of CC through CS. CA with these principles focus on higher crop productivity (inter cropping and/or crop rotations) can increase SOC and contribute to CC mitigation, but the impact will depend on the site conditions, type of cropping system, management, and the historical land use (Lal, 2015; Corbeels et al., 2019). Using CA practices to protect the soil and increase the SOM is vital for maintaining the agricultural and environmental sustainability (Chenu et al., 2019; Lal, 2015). Residue retention after harvesting can improve the physical, chemical, and biological properties of soil, and favor CS (de Figueiredo et al., 2018; Zomer et al., 2017). Soil health must be improved through the buildup of SOM content, with improvements of soil structure and tilth, enrichment of soil biotic activity and species diversity, and enhancement of soil's water retention capacity (Lal, 2019). The adoption of low C agriculture technologies based on CA has the potential to offset global emissions by 22.3% for 2021 to 2035, 25.2% from 2036 to 2050, and can mitigate 8.24 Pg C for the period from 2016 to 2050 in South America (Sá et al., 2017). The estimated potential CS by CA in Africa is 143 Tg C ha^{-1} yr^{-1} and 524 Tg CO_2 ha^{-1} yr^{-1}, which is 93 times the current CS situation of this continent (Gonzalez-Sanchez et al., 2019). However, several studies proposed for the adoption of CA practices in both tropical and temperate regions for CS (FAO, 2017; Gonzalez-Sanchez et al., 2019; Valkama et al., 2020). There are contrasting claims too, such as erroneous overestimations, trivial SOC stock increase compared to traditional practices & an inconsistent high hope on CA practices regarding mitigation potential, besides, CA practices were identified as an unnecessary policy tool (Powlson et al., 2016. Corbeels et al., 2020). Global reported values of SOC stock owing to agricultural management practices are listed in Table 3.

4. Global agricultural policies to foster carbon sequestration: an overview

CC mitigation requires low C in the ecosystem through sustainable management of ecosystem services. Perhaps, land conversion from peat lands, mangroves, old forests & marshes will be the largest releaser of minimum 260 Pg C in the atmosphere which could eventually result in a devastating CC event (Goldstein et al., 2020). Cropland Reclamation Policies (CRP) handle 0.48–4.34 Tg C due to the land transformation in Hubei, China (Tang et al., 2020). Again, including residue retention in soil as a policy was the key driver of gaining an annual net increase of 0.140 Mg C ha^{-1} in the topsoil (0–20 cm) throughout China from 1980 to 2011 (Zhao et al., 2018). To achieve "soil-based GHGS mitigation" (Paustian et al., 2016) and "self-restoring soil ecosystem"(Scholes and Scholes, 2013; Alexander et al., 2015) fruitful policy plan is mandatory. About 52%–73% C depletion rate can be abated by saving C abundant lands from conversion (Tang et al., 2020). To save the irreclaimable C from being lost (Goldstein et al., 2020) and to acquire cropland CS valuing nearly 62 Tha^{-1} at 1400 M ha land (Lal, 2016), a policy-driven priority list should be made and monetized according to the C storage capacity of ecosystem components (Zhao et al., 2018; Goldstein et al., 2020; Tang et al., 2020). The CS theme is increasing popularity and getting urgency among policymakers, scientists and farmers, so we should bring together policy and science in a common forum to create a win-win situation (Kimble et al., 2016).

As a part of the process, society remains the supreme authority for deciding whether it will invest or design effective policies including C plantings (Bryan et al., 2016), or C credits (Follett and Reed, 2010) or not. But collocation of multipurpose policies (e.g., incentives and complementary levies) is crucial in achieving the desired C within a system. In Portugal, LULC (Land Use and Land Cover) for improving forest area is projected to increase CS by 29.5% and 5% (best and worst-case scenario, respectively) by 2030 (Cunha et al., 2020). In the USA, land management practices (e.g., Cropping intensification, Organic amendments, Perennial vegetation, Biomass crops) is suggested to include in policies as they can increase CS (Post et al., 2004). The USA is estimated to increase CS by 288 Tg C yr^{-1} through the adoption of Recommended Management Practices (Lal et al., 2003). In soil and vegetation, LUC can influence future C stock changes in Europe, calculated values lie between 90 and 111 Tg C yr^{-1} by 2030 (Schulp et al., 2008). It can also be recommended government intervention on the policy to have a positive impact on augmented SOC stock (Fig. 3).

However, contrasting spatial SOC value and it is assessing accuracy and related costs are the central nexus for designing effective agreements and determining stimulus incentives between landowners and cultivators for the formation of a C market (Capon et al., 2013). In efforts to conservation actions to mitigate CC, assessing C storage and CS is vital. Some study has developed models and perspectives to assess C storage (Maraseni and Mitchell, 2016; Barré et al., 2017). But these methods are more of a scientific approach than customary use for local farmers. Most of them are used to measure the above-ground SOC storage. Heterogeneity in forest ecology is a common occurrence. Different regions require different approaches and action plans to restore SOC, so proper field condition and combination with LULC policy to foster CS are rare.

For better yield and increasing the scopes for CS by the agricultural sector, the CSA (Climate Smart Agriculture) has the opportunity for positive impact. FAO defines CSA as agriculture that sustainably increases productivity, resilience (adaptation), reduces/removes GHGs (mitigation), and enhances achievement of national food security and

Table 3
Reported values of SOC stock changing potential of different agricultural practices in the different countries of the world.

Practices	Regions	SOC stock change(s)	Reference(s)	Comments (if any)
Conservation Agriculture	i) Indo-Gangetic Plains (IGP) ii) Sub-Saharan Africa (SSA)	i) 0.16–0.49 Mg C/ha/yr ii) 0.28–0.96 Mg C/ha/yr	Powlson et al., 2016	Poor data collection, overestimations and over hyped promotion of C sequestering potential.
Agroforestry	Diverse ecosystems	i) Aboveground:0.29–15.21 Mg C/ha/yr ii) Belowground:30–300 Mg C/ha/yr	Ramachandran Nair et al., 2010	Robust potential of global C sequestration.
Agroforestry	Diverse ecosystems and biophysical conditions	8,1 ± 4,4 Mg CO_{2eq}/ha/yr	Kim et al., 2016	Robust potential of global C sequestration.
Recommended Management practices (RMPs)	Mediterranean Climate	i) Olive orchards: 1,1 Mg C/ha/yr ii) Vineyards: 0,34 Mg C/ha/yr iii) Almond orchards: 2,04 Mg C/ha/yr	Vicente-Vicente et al., 2016	Sustainable & operative tools for C capture.
Integrated crop-livestock (ICL)	Brazilian savanna (Cerrado biome)	0.82–2.58 Mg C/ha/yr	Carvalho et al., 2010	Anecdotal evidence indicates ICL as an efficient C sink
No-tillage (rotation soybean/maize)	Brazilian tropical soils	0.35 Mg C/ha/yr	Bayer et al., 2006	Potential to turn the 200Mha soils acting as a significant C sink.
Silvopastoral Systems	Colombian Amazon	1.6 Mg C/ha/yr	Landholm et al., 2019	Plausible potential to act as C sink
Reduced tillage	UK and Northwest Europe	0.310 ± 180 Mg C/ha/yr	Powlson et al., 2012	The rate is dubious to achieve, also N_2O emission can occur.

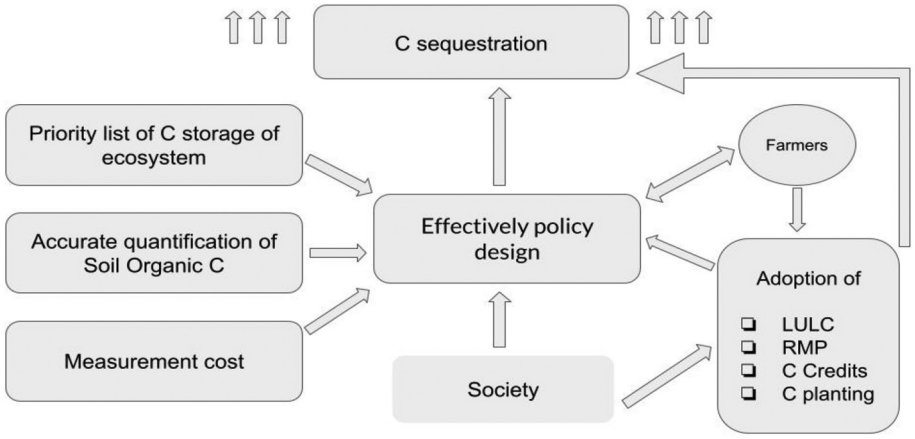


Fig. 3. Conceptual Schematic representation of the essential steps needed in effective C sequestering policy design. Unidirectional arrows indicate direct influence and bidirectional arrow specify dual role. For instance, farmers can play role in policy plans, again, policies effectiveness affect them (Bidirectional arrow). Contrarily, Society influences policy planning, implementation, and adoption by farmers, but inclusion of C planting or credits are the part and parcel of fruitful policy designing, thus, CS increases. Abbreviations: LULC = Land Use Land Cover; RMP = Recommended Management Practices.

development goals. Though the CSA and CS are different practices, combining these two will upgrade the chances of SOC storage. Burrascano et al. (2016) doubted the consequences of tree plantation in Europe aiming for both biodiversity and C storage instead of managing grasslands at low intensity while recommended for a harmonized adoption of policies addressing woodland and meadow ecologies. But the first issue can be resolved by adopting discriminatory C payments (Bryan et al., 2016).

However, there is a dearth of policies and guidelines for farmers which can incite awareness among farmers to foster CS, thus indicating the anecdotal importance of involving the farmers in the policy remains as a crucial part. Clear and accessible information on the relative benefits and costs of adopting reforestation is obligated to landholders. Incentives and co-benefits must be highlighted to the stakeholder to practice the policy (Biardeau et al., 2016). The Policy needs to be flexible enough for spontaneous participation of farmers. C Credit can be introduced as a means of incentive but in that case, initial regulations for the credit market are the top priority. According to Thamo and Pannell (2016), we need the policy continuation for optimum level of CS, otherwise, C emission from soil to the atmosphere is more likely to occur. As a result, policy failure may occur and pose a drastic impact.

5. Methods available for measuring carbon sequestration

Plant shoot and root C stocks along with CS in agricultural and forest soils are strategic to mitigate CC and for improving food security (Lal, 2004; Powlson et al., 2016). Improved land use and management practices for C mitigation need robust quantification and monitoring technologies that should be reliable and accurate (Paustian et al., 2016). It is crucial to measure and determine the spatio-temporal fluctuations of C stock through direct field measurements, remote sensing, and model-based tools (Petrokofsky et al., 2012). Besides, the obtained information can contribute to robust Measure Report and Verification (MRV) platforms to support international and national initiatives to increase SOC, REDD+ programs, support policy efforts on CC mitigation and C credit trading schemes (Hurtt et al., 2019; Smith et al., 2020; Ochieng et al., 2016). However, affordability of either methodology may vary according to science policy of DC.

5.1. Direct measurements

Direct field measurements to assess SOC stock changes are more frequent in plot scale studies (experiments), where deformed samples to measure C content on the fine earth fraction (<2 mm) and undeformed samples for bulk density are collected from a determined depth of the soil profile (FAO, 2019). Spatial and temporal variations should be considered to obtain reliable C stock changes in long term field experiments (FAO, 2019), otherwise, erroneous data can be produced. Deeper soil sampling (100 cm) is recommended for crops with deep (tap) roots, as they can accumulate C in deeper soil depth, but this is costly & laborious (FAO, 2019; Paustian et al., 2016).

Spectroscopic methods are employed for direct measurements in both small- scale (field and lab) and large-scale (landscapes) systems as they are less time-consuming, cost-effective, non-destructive and don't take in use of chemicals (Smith et al., 2020; Stevens et al., 2006). These methods are based on the reflectance of light & soil absorbs a specific wavelength, then, under spectral library and calibrations, they can predict soil properties (Stevens et al., 2008). SOC can be spectrally measured with a reasonable accuracy level, but less accurate than the conventional chemical lab analyses. As a larger number of samples can be processed, it can offset the trivial loss of precision (Stevens et al., 2006). Different environments and spatial scales require different VNIR techniques for instance, Laboratory Spectroscopy (LS), Portable field Spectroscopy (PS) and Remote Spectroscopy (RS). The RS is based on air or space-borne sensors, while LS and PS are grounded on point spectrometry (ground-based sensors) (Stevens et al., 2008).

Eddy Covariance (EC) flux systems can measure CO_2 exchange between ecosystems and atmosphere for longer lapse of time using sonic anemometer and infrared gas analyzer (IRGA), which is mostly used in steady atmosphere, homogeneous vegetations, and flat terrains (Baldocchi, 2003). The EC can quantify the impacts of agricultural management practices, agro-climatic conditions, and crop rotation on net ecosystem exchange (NEE), CO_2 emitted by agricultural machineries, and their influences on the flux and CO_2 concentrations in the atmosphere (Davis et al., 2010; Taylor et al., 2013). Due to low turnover in the soil compartment, net changes in SOC pools are relatively small in short periods (<5 years), hence, uncertainties in measurements may occur (Smith et al., 2020). However, studies with EC coupled with direct measuring of SOC stock change can improve the understanding of short- and long-term effects of managements and climate on net ecosystem C (Ferster et al., 2015; Leifeld et al., 2011).

C stored on forests above-ground biomass (AGB) can be estimated by allometric equations, where field measurements of variables (such as diameter and height) are used to assess attributes that are more difficult to obtain (biomass). It provides relatively accurate estimates, but facilitates large-scale estimations (Phillips et al., 2002). Yet, direct measurements of AGB are limited for small zones and more studies are required for country and region-specific allometric equations (Petrokofsky et al., 2012; Singh et al., 2011). Therefore, allometric equations might be applicable in systems where trees are the major components e.g. agroforestry.

5.2. Remote sensing

Remote sensing for mapping SOC is equally accurate and economic, requires different mapping and sampling procedures for different areas and crop fields, still, it has high-resolution ability for predicting SOC distribution in specific sites (Chatterjee et al., 2009). It can also predict changes at large scales, for instance, vegetation patterns and land-use changes, thus, can identify high potential areas for CS (Jaber et al., 2011; Rogge et al., 2018). Landsat satellite imagery has continuous coverage, cost-effectiveness, and image accessibility, might be applied successfully for the validation and monitoring of grasslands and crop intensity for CS estimation and C credit trading schemes (Watts et al., 2009). Combined application of remote and in situ or point data is obligatory to derive high resolution and accurate SOC maps over the world (Smith et al., 2020).

Optical satellite sensors provide spatial vegetation information that can be integrated to ground-based measurements to estimate C stocks on forest areas, and even make projections for potential CS (Ni-Meister et al., 2010; Hurtt et al., 2019). Lidar is an active remote sensing technique that is well acknowledged for providing high-resolution, 3-D information on vertical and horizontal forest structure, above-ground biomasses, and underlying topography (Simonson et al., 2016).

5.3. Model-based estimation

We can use modeling approaches at various scales, both on project scale (individual field) and national scales, evaluate the efficacy of increasing SOC on management practices over an extended time span and accounting in annual inventory GHGs reports (Oelbermann and Voroney, 2011; FAO, 2019). Empirical models are the easiest way for some countries to predict SOC change for their national inventory of GHGs, and widely known as the Tier 1 method from IPCC guidelines (default value) (IPCC, 2006). Some regional studies may be needed to readjust model parameters from the IPCC method. Process-based models can simulate the C dynamics from environmental variables, land use and agricultural practices (Paustian et al., 2019). Those soil and ecosystems models are more complex than the empirical models, the ecosystems approach are locally calibrated and require more data resources for modeling which might be a limitation, but facilitates accurate estimation (FAO, 2019).

The FullCAM model developed by Australia's National Carbon Accounting System (NCAS) the Australian Greenhouse Office (AGO), integrates biomass, decomposition, soil C models, and accounting tools to provide a single model capable of carbon accounting in afforestation, reforestation, deforestation and AFS (Richards, 2001). It includes all C pools and allocations to ensure that there are no significant occasions of double counting or omissions in accounting. The FullCAM model allows a fine spatial resolution (grids) of 1 ha, providing a capacity for national and project scale modeling, in response to specific activities and timing (Richards, 2001). The RothC is a sub-model from FullCAM to predict the turnover of SOC, that uses a monthly time step, it is one of the widely used in the world and has a simpler structure than other models (Smith et al., 1997). It needs a few easily obtainable inputs, such as climate, soil, and the decomposability of the incoming plant material parameters (Coleman and Jenkinson, 2014).

The Century model can provide long-term trends and help to identify factors leading to a buildup or cost of SOC because of land management practices and land-use changes (Oelbermann and Voroney, 2011). This model uses soil-plant–climate interactions to describe the soil CN dynamics, assessment of organic matter addition through agricultural practices and simulate biomass production above and below-ground as a function of nutrients and soil characteristics (Parton et al., 1988; Smith et al., 2009).The C-TOOL is a dynamic soil model parameterized and validated utensil that allows simulations on medium to long-term changes in SOC under agricultural management in temperate soils, using fewer parameters and input data (Taghizadeh-Toosi et al., 2014). The denitrification-decomposition (DNDC) model is a process-oriented model to assess the soil C and N biogeochemistry dynamics, with a simulated period from several days to centuries (Li, 1996). The Daycent model (soil-based approach) can estimate both soil C stock changes and soil CH_4 and N_2O emissions (Del Grosso et al., 2001). The mathematical model *ecosys* is used to predict transformation and transfer of water, oxygen, C and nutrients under changes on climate and management (e.g., changes on soil organic matter on tillage and fallowing) (Grant, 1997). Nevertheless, the use or implementation of complex models for SOC mainly depends on the available data, their periodicity in the measurements, which sometimes limits the use of these approaches. There are methodologies to believe to estimate SOC in a simple way i.e., IPCC (2006) guidelines which using changes in carbon stocks; and other models based on net carbon fluxes in agricultural/livestock soils (Vleeshouwers and Verghagen, 2002; Petersen et al., 2013; Batalla et al., 2015; Ricard and Viglizzo, 2020). As a whole, all the methods to estimate SOC should be chosen by specific measurement needs and applications (Fig. 4), so the choice of an instrument or measurement techniques depend on the researchers' need and resources, such as the project objective and funding (Chatterjee et al., 2009).

6. Concluding remarks and recommendations

We conclude SOC is the founding block of sustainable agriculture. CO_2 reduction as a CC adaptive solution has become a standard aspect in line with the Paris Agreement objectives and SDGs; but, for

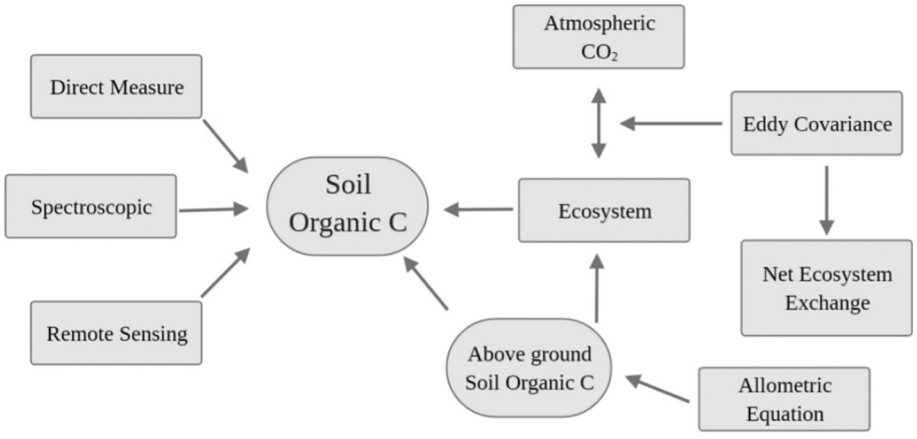


Fig. 4. Conceptual diagram showing different methods of measuring SOC. For example, eddy covariance can measure both net ecosystem exchange and atmospheric CO_2 level, allometric equations can predict biomass C storage.

evaluation of its capacity, practical assessment of agricultural practices that influence C storage in the agroecosystems is essential (Keel et al., 2019). Management practices for accelerating CS in agroecosystems are highly climate and time-dependent. Although C credits or payments are not in vogue, Govt. incentives may promote C planting or encourage farmers to shift in sustainable low-carbon agricultural practices and production intensification, thus, it will attract investments which will eventually lead to the reduction of GHGs for per unit of product and pressure on the environment (Cardoso et al., 2016). However, we recommend the following things:

i) Grasses and cereals should be added in the cropping systems with an average 76% C enchanting abilities through shoots.
ii) No-tillage or bare soil approach is an over-promoted method for CS. It can boost the SOC stock in the topsoil (0–10 cm) for the short-term in certain pedo-climatic conditions, but long-term experiments showed almost the same SOC stock compared to plow tilling.
iii) Agroforestry is one of the most promising options for augmenting C storage & help in stable aggregate formation in both arable lands & grasslands of tropical and temperate zones. In livestock systems, conversion from pastures to agroforestry is a promising management strategy in DC, since not only is an interesting mitigation strategy, but also one of the adaptation strategies with an important beneficial effect, especially on heat stress. This last point is important for the countries participating in this work, where heat stress in animals is one of the main impacts of CC, generating important economic losses in this type of production. However, conversion from pasture to agroforestry will be beneficial.
iv) Farmers from DC should be considered as the key driver for effective policy implementation for SCS. CO_2 comprises almost 65% of total GHGSs, C plantings can be done to capture it via farmers if they consider it affordable & relatively cheaper, get C credits.
v) Crop yield and SOC stocks are significantly allied e.g., a meta-analysis of 32 field studies showed around 1.4% increase in grain yield was coupled with 0.4% expansion in SOC stock (Soussana et al., 2019). So, to obtain better crop production and ensure sustainable food available for all the regions, we must have to stretch out climate-smart agricultural management practices for augmenting SOC stocks.
vi) Animal farming can be a major source of GHG emissions. However, there are still a significant number of strategies and policies to compensate these emissions through C capture and storage, and in some cases to achieve zero carbon production systems. Currently, in developing countries, this issue is gaining interest not only from governments, but also from the private sector. In our countries, there are still many process technologies to be adopted by producers, allowing them to improve the efficiency of agricultural production systems without having a negative impact on emissions and, in some cases, increasing and/or restoring the SOC.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table A1
Production of commodities per country (millions of metric tonnes). NR = Not Ranked by FAO.
Source: (FAO, 2021).

Commodity	Country production (mill of metric tonnes)				
	Argentina	Bangladesh	Brazil	Mexico	Nigeria
Barley	5.12	NR	NR	NR	NR
Cassava & Yams	NR	NR	17.50	NR	109.25
Chillies and peppers, green	NR	NR	NR	3.24	NR
Jute	NR	1.60	NR	NR	NR
Maize	56.86	3.57	101.14	27.23	11.00
Meat, cattle	3.14	NR	10.20	NR	NR
Milk, whole fresh cow	10.34	NR	35.89	12.28	NR
Potatoes	2.21	9.70	3.70	NR	NR
Rice, paddy	1.6	54.60	10.40	NR	8.40
Rice, paddy (rice milled equivalent)	NR	36.40	6.91	NR	5.63
Sorghum	NR	NR	NR	6.67	4.35
Soybeans	55.26	NR	114.27	NR	NR
Sugar cane	17.65	3.14	752.90	59.33	NR
Sunflower seed	3.83	NR	NR	NR	NR
Tomato	NR	NR	NR	4.27	NR
Wheat	19.46	NR	NR	3.24	NR

References

Abdalla, K., Chivenge, P., Ciais, P., Chaplot, V., 2016. No-tillage lessens soil CO_2 emissions the most under arid and sandy soil conditions: results from a meta-analysis. Biogeosciences 13, 3619–3633. https://doi.org/10.5194/bg-13-3619-2016.

Acir, N., Günal, H., Çelik, İ., Barut, Z.B., Budak, M., Kılıç, Ş., 2020. Effects of long-term conventional and conservational tillage systems on biochemical soil health indicators in the Mediterranean region. Arch. Agron. Soil Sci., 1–14 https://doi.org/10.1080/03650340.2020.1855327.

Aertsens, J., De Nocker, L., Gobin, A., 2013. Valuing the carbon sequestration potential for European agriculture. Land Use Policy 31, 584–594. https://doi.org/10.1016/j.landusepol.2012.09.003.

Ahmed, J., Almeida, E., Aminetzah, D., Denis, N., Henderson, K., Katz, J., Kitchel, H., Mannion, P., 2020. Agriculture and climate change: reducing emissions through improved farming practices. Agric. Clim. Chang. 1, 9–10.

Albrecht, A., Kandji, S.T., 2003. Carbon sequestration in tropical agroforestry systems. Agric. Ecosyst. Environ. 99, 15–27. https://doi.org/10.1016/S0167-8809(03)00138-5.

Alexander, P., Paustian, K., Smith, P., Moran, D., 2015. The economics of soil c sequestration and agricultural emissions abatement. Soil 1, 331–339. https://doi.org/10.5194/soil-1-331-2015.

Alvarez, R., Berhongaray, G., Gimenez, A., 2021. Are grassland soils of the pampas sequestering carbon? Sci. Total Environ. 763, 142978. https://doi.org/10.1016/j.scitotenv.2020.142978.

Alves, B.J.R., Madari, B.E., Boddey, R.M., 2017. Integrated crop–livestock–forestry systems: prospects for a sustainable agricultural intensification. Nutr. Cycl. Agroecosyst. 108, 1–4. https://doi.org/10.1007/s10705-017-9851-0.

Angers, D.A., Eriksen-Hamel, N.S., 2008. Full-inversion tillage and organic carbon distribution in soil profiles: a meta-analysis. Soil Sci. Soc. Am. J. 72, 1370–1374. https://doi.org/10.2136/sssaj2007.0342.

Balbino, L.C., Barcellos, A.D.O., Stone, L.F., 2011. Marco referencial: integração lavoura-pecuária-floresta. Embrapa Cerrados-Livro científico (ALICE)https://www.alice.cnptia.embrapa.br/bitstream/doc/923530/1/balbino01.pdf. (Accessed 13 March 2021).

Baldocchi, D., 2003. Assessing ecosystem carbon balance: problems and prospects of the eddy covariance technique. Glob. Chang. Biol. 9, 479–492. https://doi.org/10.1046/j.1365-2486.2003.00629.x.

Barré, P., Angers, D., Basile-Doelsch, I., Bispo, A., Cécillon, L., Chenu, C., Chevallier, T., Derrien, D., Eglin, T., Pellerin, S., 2017. Ideas and perspectives: can we use the soil carbon saturation deficit to quantitatively assess the soil carbon storage potential, or should we explore other strategies? Biogeosci. Discuss., 1–12 https://doi.org/10.5194/bg-2017-395.

Batalla, I., Knudsen, M.T., Mogensen, L., Hierro, Ó. Del, Pinto, M., Hermansen, J.E., 2015. Carbon footprint of milk from sheep farming systems in Northern Spain including soil carbon sequestration in grasslands. J. Clean. Prod. 104, 121–129. https://doi.org/10.1016/j.jclepro.2015.05.043.

Bayer, C., Martin-Neto, L., Mielniczuk, J., Pavinato, A., Dieckow, J., 2006. Carbon sequestration in two Brazilian Cerrado soils under no-till. Soil Tillage Res. 86, 237–245. https://doi.org/10.1016/j.still.2005.02.023.

Bellarby, J., Foereid, B., Hastings, A.F.S.J., Smith, P., 2008. Cool farming: climate impacts of agriculture and mitigation potential. Greenpeace Int. 44https://www.greenpeace.org/usa/research/cool-farming-climate-impacts/. (Accessed 23 April 2021).

Bennett, E.M., Peterson, G.D., Gordon, L.J., 2009. Understanding relationships among multiple ecosystem services. Ecol. Lett. 12, 1394–1404. https://doi.org/10.1111/j.1461-0248.2009.01387.x.

Biardeau, L., Coates, R.C., Keerati, R., Litke, S., 2016. Soil health and carbon sequestration in US croplands: a policy analysis. http://food.berkeley.edu/wpcontent/uploads/2016/05/GSPPCarbon_03052016_FINAL.pdf. (Accessed 23 March 2021).

Blanco-Canqui, H., Lal, R., 2009. Response to the 'Comments on "No-tillage and soil-profile carbon sequestration: an on-farm assessment"'. Soil Sci. Soc. Am. J. 73, 690–691. https://doi.org/10.2136/sssaj2008.0341l.

Bolsa de Comercio de Rosario, 2018. Bolsa de Comercio de Rosario. https://www.bcr.com.ar/es. (Accessed 23 April 2021).

Bryan, B.A., Runting, R.K., Capon, T., Perring, M.P., Cunningham, S.C., Kragt, M.E., Nolan, M., Law, E.A., Renwick, A.R., Eber, S., Christian, R., Wilson, K.A., 2016. Designer policy for carbon and biodiversity co-benefits under global change. Nat. Clim. Chang. 6, 301–305. https://doi.org/10.1038/nclimate2874.

Burrascano, S., Chytrý, M., Kuemmerle, T., Giarrizzo, E., Luyssaert, S., Sabatini, F.M., Blasi, C., 2016. Current European policies are unlikely to jointly foster carbon sequestration and protect biodiversity. Biol. Conserv. 201, 370–376. https://doi.org/10.1016/j.biocon.2016.08.005.

Capon, T., Harris, M., Reeson, A., 2013. The design of markets for soil carbon sequestration. Econ. Pap. 32, 161–173. https://doi.org/10.1111/1759-3441.12034.

Cárdenas, A., Moliner, A., Hontoria, C., Ibrahim, M., 2019. Ecological structure and carbon storage in traditional silvopastoral systems in Nicaragua. Agrofor. Syst. 93, 229–239. https://doi.org/10.1007/s10457-018-0234-6.

Cardil, A., De-Miguel, S., Silva, C.A., Reich, P.B., Calkin, D., Brancalion, P.H., Liang, J., 2020. Recent deforestation drove the spike in Amazonian fires. Environ. Res. Lett. 15, 121003.

Cardoso, A.S., Berndt, A., Leytem, A., Alves, B.J.R., de Carvalho, I. das N.O., de Barros Soares, L.H., Urquiaga, S., Boddey, R.M., 2016. Impact of the intensification of beef production in Brazil on greenhouse gas emissions and land use. Agric. Syst. 143, 86–96. https://doi.org/10.1016/j.agsy.2015.12.007.

Carvalho, J.L.N., Raucci, G.S., Cerri, C.E.P., Bernoux, M., Feigl, B.J., Wruck, F.J., Cerri, C.C., 2010. Impact of pasture, agriculture and crop-livestock systems on soil C stocks in Brazil. Soil Tillage Res. 110, 175–186. https://doi.org/10.1016/j.still.2010.07.011.

Carvalho, J.L.N., Raucci, G.S., Frazão, L.A., Cerri, C.E.P., Bernoux, M., Cerri, C.C., 2014. Crop-pasture rotation: a strategy to reduce soil greenhouse gas emissions in the Brazilian Cerrado. Agric. Ecosyst. Environ. 183, 167–175. https://doi.org/10.1016/j.agee.2013.11.014.

Chará, J., Rivera, J., Barahona, R., Murgueitio, R.E., Deblitz, C., Reyes, E., Mauricio, R.M., Molina, J.J., Flores, M., Zuluaga, A., 2017. Intensive silvopastoral systems: economics and contribution to climate change mitigation and public policies. In: Montagnini, F. (Ed.), Integrating Landscapes: Agroforestry for Biodiversity Conservation and Food Sovereignty. Springer International Publishing, pp. 395–416 https://doi.org/10.1007/978-3-319-69371-2_16.

Chatterjee, A., Lal, R., Wielopolski, L., Martin, M.Z., Ebinger, M.H., 2009. Evaluation of different soil carbon determination methods. CRC. Crit. Rev. Plant Sci. 28, 164–178. https://doi.org/10.1080/07352680902776556.

Chenu, C., Angers, D.A., Barré, P., Derrien, D., Arrouays, D., Balesdent, J., 2019. Increasing organic stocks in agricultural soils: knowledge gaps and potential innovations. Soil Tillage Res. 188, 41–52. https://doi.org/10.1016/j.still.2018.04.011.

Coleman, K., Jenkinson, D., 2014. RothC - A Model for the Turnover of Carbon in Soil. Model Description and Windows User Guide. Evaluation of Soil Organic Matter Models: Using Existing Long-term Datasets. Lawes Agricultural Trust, Harpenden, Herts, UK.

Conant, R.T., Paustian, K., Elliott, E.T., 2001. Grassland management and conversion into grassland: effects on soil carbon. Ecol. Appl. 11, 343–355. https://doi.org/10.1890/1051-0761(2001)011[0343:GMACIG]2.0.CO;2.

Conant, R.T., Cerri, C.E.P., Osborne, B.B., Paustian, K., 2017. Grassland management impacts on soil carbon stocks: a new synthesis. Ecol. Appl. 27, 662–668. https://doi.org/10.1002/eap.1473.

Conceição, M.C.G. da, S. Matos, E., Bidone, E.D., Rodrigues, R. de A.R., Cordeiro, R.C., 2017. Changes in soil carbon stocks under integrated crop-livestock-forest system in the Brazilian Amazon Region. Agric. Sci. 08, 904–913. https://doi.org/10.4236/as.2017.89066.

Conrad, K., Dalal, R.C., Fujinuma, R., Menzies, N.W., 2018. Soil organic carbon and nitrogen sequestration and turnover in aggregates under subtropical leucaena-grass pastures. Soil Res. 56, 632–647. https://doi.org/10.1071/SR18016.

Corbeels, M., Cardinael, R., Naudin, K., Guibert, H., Torquebiau, E., 2019. The 4 per 1000 goal and soil carbon storage under agroforestry and conservation agriculture systems in sub-Saharan Africa. Soil Tillage Res. 188, 16–26. https://doi.org/10.1016/j.still.2018.02.015.

Corbeels, M., Cardinael, R., Powlson, D., Chikowo, R., Gerard, B., 2020. Carbon sequestration potential through conservation agriculture in Africa has been largely overestimated: comment on: "Meta-analysis on carbon sequestration through conservation agriculture in Africa". Soil Tillage Res. 196, 104300. https://doi.org/10.1016/j.still.2019.104300.

Costa, M.P., Schoeneboom, J.C., Oliveira, S.A., Viñas, R.S., de Medeiros, G.A., 2018. A socio-eco-efficiency analysis of integrated and non-integrated crop-livestock-forestry systems in the Brazilian Cerrado based on LCA. J. Clean. Prod. 171, 1460–1471. https://doi.org/10.1016/j.jclepro.2017.10.063.

Cunha, J., Campos, F.S., David, J., Padmanaban, R., 2020. Carbon Sequestration Scenarios in Portugal: Which Way to Go Forward? https://doi.org/10.21203/rs.3.rs-43518/v1

Cusack, D.F., Kazanski, C.E., Hedgpeth, A., Chow, K., Cordeiro, A.L., Karpman, J., Ryals, R., 2021. Reducing climate impacts of beef production: a synthesis of life cycle assessments across management systems and global regions. Glob. Chang. Biol. https://doi.org/10.1111/gcb.15509.

Data, 2019. Resource trade. https://resourcetrade.earth/. (Accessed 23 April 2021).

Davis, P.A., Brown, J.C., Saunders, M., Lanigan, G., Wright, E., Fortune, T., Burke, J., Connolly, J., Jones, M.B., Osborne, B., 2010. Assessing the effects of agricultural management practices on carbon fluxes: spatial variation and the need for replicated estimates of Net Ecosystem Exchange. Agric. For. Meteorol. 150, 564–574. https://doi.org/10.1016/j.agrformet.2010.01.021.

de Figueiredo, C.C., de Oliveira, A.D., dos Santos, I.L., Ferreira, E.A.B., Malaquias, J.V., de Sá, M.A.C., de Carvalho, A.M., dos Santos, J. de D.G., 2018. Relationships between soil organic matter pools and nitrous oxide emissions of agroecosystems in the Brazilian Cerrado. Sci. Total Environ. 618, 1572–1582. https://doi.org/10.1016/j.scitotenv.2017.09.333.

De Moraes, A., Carvalho, P.C. de F., Anghinoni, I., Lustosa, S.B.C., Costa, S.E.V.G. de A., Kunrath, T.R., 2014. Integrated crop-livestock systems in the Brazilian subtropics. Eur. J. Agron. 57, 4–9. https://doi.org/10.1016/j.eja.2013.10.004.

de Vries, W., Solberg, S., Dobbertin, M., Sterba, H., Laubhann, D., van Oijen, M., Evans, C., Gundersen, P., Kros, J., Wamelink, G.W.W., Reinds, G.J., Sutton, M.A., 2009. The impact of nitrogen deposition on carbon sequestration by European forests and heathlands. For. Ecol. Manag. 258, 1814–1823. https://doi.org/10.1016/j.foreco.2009.02.034.

Del Grosso, S., Parton, W., Mosier, A., Hartman, M., Brenner, J., Ojima, D., Schimel, D., et al., 2001. Simulated interaction of carbon dynamics and nitrogen trace gas fluxes using the DAYCENT model. Modeling Carbon and Nitrogen Dynamics for Soil Management, pp. 303–332.

Derpsch, R., Friedrich, T., Kassam, A., Hongwen, L., 2010. Current status of adoption of no-till farming in the world and some of its main benefits. Int. J. Agric. Biol. Eng. 3, 1–25. https://doi.org/10.3965/j.issn.1934-6344.2010.01.001-025.

Dimassi, B., Mary, B., Wylleman, R., Labreuche, J.Ô., Couture, D., Piraux, F., Cohan, J.P., 2014. Long-term effect of contrasted tillage and crop management on soil carbon dynamics during 41 years. Agric. Ecosyst. Environ. 188, 134–146. https://doi.org/10.1016/j.agee.2014.02.014.

Dold, C., Thomas, A.L., Ashworth, A.J., Philipp, D., Brauer, D.K., Sauer, T.J., 2019. Carbon sequestration and nitrogen uptake in a temperate silvopasture system. Nutr. Cycl. Agroecosyst. 114, 85–98. https://doi.org/10.1007/s10705-019-09987-y.

Domiciano, L.F., Pedreira, B.C., da Silva, N.M.F., Mombach, M.A., Chizzotti, F.H.M., Batista, E.D., Carvalho, P., Cabral, L.S., Pereira, D.H., do Nascimento, H.L.B., 2020. Agroforestry

systems: an alternative to intensify forage-based livestock in the Brazilian Amazon. Agrofor. Syst. 94, 1839–1849. https://doi.org/10.1007/s10457-020-00499-1.
E.P.A., 2021. Greenhouse gas reporting program report verification. U.S. Environmental Protection Agency, Washington, D.Chttps://www.epa.gov/sites/production/files/2021/documents/ghgrp_verification_factsheet.pdf. (Accessed 23 April 2021).
FAO, 2011. The state of the world's land and water resources for food and agriculture (SOLAW): managing systems at risk. Food and Agriculture Organization of the United Nations (FAO); London, UK: Earthscan, Rome, Italyhttp://www.fao.org/docrep/017/i1688e/i1688e.pdf. (Accessed 23 April 2021).
FAO, 2017. Conservation agriculture. FAO. http://www.fao.org/documents/card/en/c/981ab2a0-f3c6-4de3-a058-f0df6658e69f/. (Accessed 23 April 2021).
FAO, 2019. Measuring and modelling soil carbon stocks and stock changes in livestock production systems: guidelines for assessment (draft for public review). Livest. Environ. Assess. Perform. Partnership 170, 170. http://www.fao.org/3/ca2934en/CA2934EN.pdf. (Accessed 23 April 2021).
FAO, 2020a. FAOSTAT database. http://faostat3.fao.org/home/index.html#DOWNLOAD. (Accessed 23 April 2021).
FAO, 2020b. Technical specifications and country guidelines for Global Soil Organic Carbon Sequestration Potential Map (GSOCseq). Pillar 4 Work. Gr. INSII. http://www.fao.org/3/cb0353en/cb0353en.pdf. (Accessed 23 April 2021).
FAOSTAT, 2018. Food and Agriculture Organization of the United Nations (FAO). FAOSTAT Database. http://faostat.fao.org/. (Accessed 23 April 2021).
Feng, Q., An, C., Chen, Z., Wang, Z., 2020. Can deep tillage enhance carbon sequestration in soils? A meta-analysis towards GHG mitigation and sustainable agricultural management. Renew. Sust. Energ. Rev. 133, 110293. https://doi.org/10.1016/j.rser.2020.110293.
Ferster, C.J., Trofymow, J.A.T., Coops, N.C., Chen, B., Black, T.A., 2015. Comparison of carbon-stock changes, eddy-covariance carbon fluxes and model estimates in coastal douglas-fir stands in British Columbia. For. Ecosyst. 2, 13. https://doi.org/10.1186/s40663-015-0038-3.
Follett, R.F., Reed, D.A., 2010. Soil carbon sequestration in grazing lands: societal benefits and policy implications. Rangel. Ecol. Manag. 63, 4–15. https://doi.org/10.2111/08-225.1.
Friedrich, T., Derpsch, R., Kassam, A., 2017. Overview of the global spread of conservation agriculture. Sustain. Dev. Org. Agric. Hist. Perspect. 8. https://doi.org/10.1201/9781315365800.
Galdos, M.V., Pires, L.F., Cooper, H.V., Calonego, J.C., Rosolem, C.A., Mooney, S.J., 2019. Assessing the long-term effects of zero-tillage on the macroporosity of Brazilian soils using X-ray Computed Tomography. Geoderma 337, 1126–1135. https://doi.org/10.1016/j.geoderma.2018.11.031.
Gerber, P.J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., Falcucci, A., Tempio, G., 2013. Tackling climate change through livestock – a global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations (FAO, Rome) http://www.fao.org/3/i3437e/i3437e.pdf. (Accessed 23 April 2021).
Gmach, M.R., Dias, B.O., Silva, C.A., Nóbrega, J.C.A., Lustosa-Filho, J.F., Siqueira-Neto, M., 2018. Soil organic matter dynamics and land-use change on Oxisols in the Cerrado, Brazil. Geoderma Reg. 14, 178. https://doi.org/10.1016/j.geodrs.2018.e00178.
Goldstein, A., Turner, W.R., Spawn, S.A., Anderson-Teixeira, K.J., Cook-Patton, S., Fargione, J., Gibbs, H.K., Griscom, B., Hewson, J.H., Howard, J.F., Ledezma, J.C., Page, S., Koh, L.P., Rockström, J., Sanderman, J., Hole, D.G., 2020. Protecting irrecoverable carbon in Earth's ecosystems. Nat. Clim. Chang. 10, 287–295. https://doi.org/10.1038/s41558-020-0738-8.
Gonzalez-Sanchez, E.J., Veroz-Gonzalez, O., Conway, G., Moreno-Garcia, M., Kassam, A., Mkomwa, S., Ordoñez-Fernandez, R., Triviño-Tarradas, P., Carbonell-Bojollo, R., 2019. Meta-analysis on carbon sequestration through Conservation Agriculture in Africa. Soil Tillage Res. 190, 22–30. https://doi.org/10.1016/j.still.2019.02.020.
Grant, R.F., 1997. Changes in soil organic matter under different tillage and rotation: mathematical modeling in ecosys. Soil Sci. Soc. Am. J. 61, 1159–1175. https://doi.org/10.2136/sssaj1997.03615995006100040023x.
Gupta, M.K., Sharma, S.D., 2013. Sequestered organic carbon status in the soils under grassland in Uttarakhand State, India. Appl. Ecol. Environ. Sci. 1, 7–9. https://doi.org/10.12691/aees-1-1-2.
Gupta, M., Sharma, S., 2014. Sequestered organic carbon stock in the soils under different land uses in Uttarakhand State of India. Life Sci. 141, 718–725.
Herrero, M., Henderson, B., Havlík, P., Thornton, P.K., Conant, R.T., Smith, P., Wirsenius, S., Hristov, A.N., Gerber, P., Gill, M., Butterbach-Bahl, K., Valin, H., Garnett, T., Stehfest, E., 2016. Greenhouse gas mitigation potentials in the livestock sector. Nat. Clim. Chang. 6, 452–461. https://doi.org/10.1038/nclimate2925.
Hossain, M.I., Sarker, M., Haque, M.A., 2015. Status of conservation agriculture based tillage technology for crop production in Bangladesh. Bangladesh J. Agric. Res. 40, 235–248. https://doi.org/10.3329/bjar.v40i2.24561.
Houghton, R.A., 2012. Carbon emissions and the drivers of deforestation and forest degradation in the tropics. Curr. Opin. Environ. Sustain. 4, 597–603. https://doi.org/10.1016/j.cosust.2012.06.006.
Houghton, R.A., Nassikas, A.A., 2017. Global and regional fluxes of carbon from land use and land cover change 1850–2015. Glob. Biogeochem. Cycles 31, 456–472. https://doi.org/10.1002/2016GB005546.
Hui, D., Deng, Q., Tian, H., Luo, Y., 2015. Climate change and carbon sequestration in forest ecosystems. In: Chen, W.-Y. (Ed.), Handbook of Climate Change Mitigation and Adaptation, pp. 1–40 https://doi.org/10.1007/978-1-4614-6431-0_13-2.
Hurtt, G., Zhao, M., Sahajpal, R., Armstrong, A., Birdsey, R., Campbell, E., Dolan, K., Dubayah, R., Fisk, J.P., Flanagan, S., Huang, C., Huang, W., Johnson, K., Lamb, R., Ma, L., Marks, R., O'Leary, D., O'Neil-Dunne, J., Swatantran, A., Tang, H., 2019. Beyond MRV: high-resolution forest carbon modeling for climate mitigation planning over Maryland, USA. Environ. Res. Lett. 14, 45013. https://doi.org/10.1088/1748-9326/ab0bbe.
IBGE - Brazilian Institute of Geography and Statistics, 2017. Censo Agropecuário 2017 (Agricultural census 2017) - area with no till in Brazil (hectares). Sistema IBGE de Recuperação Automática – SIDRAhttps://sidra.ibge.gov.br/tabela/3939#resultado. (Accessed 23 April 2021).
IPCC, 2006. IPCC guidelines for national greenhouse gas inventories. Intergovernmental Panel of Climate Change (IPCC), National Greenhouse gas Inventories Programme http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html. (Accessed 23 April 2021).
IPCC - International Panel of Climate Change, 2013. Summary for policymakers. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. . Cambridge University Press, pp. 1–30 https://doi.org/10.1017/CBO9781107415324.004.
IPCC - International Panel of Climate Change, 2014. In: Core Writing Team, Pachauri, R.K., Meyer, L.A. (Eds.), Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland https://www.ipcc.ch/site/assets/uploads/2018/05/SYR_AR5_FINAL_full_wcover.pdf. (Accessed 23 April 2021) (151 pp.).
Jaber, S.M., Lant, C.L., Al-Qinna, M.I., 2011. Estimating spatial variations in soil organic carbon using satellite hyperspectral data and map algebra. Int. J. Remote Sens. 32, 5077–5103. https://doi.org/10.1080/01431161.2010.494637.
Jantke, K., Hartmann, M.J., Rasche, L., Blanz, B., Schneider, U.A., 2020. Agricultural greenhouse gas emissions: knowledge and positions of German farmers. Land 9, 1–13. https://doi.org/10.3390/LAND9050130.
Kassam, A., Friedrich, T., Derpsch, R., Kienzle, J., 2015. Overview of the worldwide spread of conservation agriculture. Field Actions Science Reports [Online] https://journals.openedition.org/factsreports/3966. (Accessed 23 April 2021) (Vol. 8/2015. Online since 26 September 2015, connection on 30 September 2016).
Keel, S.G., Anken, T., Büchi, L., Chervet, A., Fliessbach, A., Flisch, R., Huguenin-Elie, O., Mäder, P., Mayer, J., Sinaj, S., Sturny, W., Wüst-Galley, C., Zihlmann, U., Leifeld, J., 2019. Loss of soil organic carbon in Swiss long-term agricultural experiments over a wide range of management practices. Agric. Ecosyst. Environ. 286, 106654. https://doi.org/10.1016/j.agee.2019.106654.
Kemmitt, S.J., Lanyon, C.V., Waite, I.S., Wen, Q., Addiscott, T.M., Bird, N.R.A., O'Donnell, A.G., Brookes, P.C., 2008. Mineralization of native soil organic matter is not regulated by the size, activity or composition of the soil microbial biomass-a new perspective. Soil Biol. Biochem. 40, 61–73. https://doi.org/10.1016/j.soilbio.2007.06.021.
Kim, D.G., Kirschbaum, M.U.F., Beedy, T.L., 2016. Carbon sequestration and net emissions of CH_4 and N_2O under agroforestry: synthesizing available data and suggestions for future studies. Agric. Ecosyst. Environ. 226, 65–78. https://doi.org/10.1016/j.agee.2016.04.011.
Kimble, J.M., Lal, R., Follett, R.F., 2016. Agricultural practices and policies for carbon sequestration in soil. Agric. Pract. Policies Carbon Sequestration Soil https://doi.org/10.2135/cropsci2003.1895.
Kishwan, J., General, D., Pandey, R., Dadhwal, V., 2009. Indian Council of Forestry Research and Education contribution as a carbon sink. Tech. Pap. 130, 1–12.
Köchy, M., Hiederer, R., Freibauer, A., 2015. Global distribution of soil organic carbon – part 1: masses and frequency distributions of SOC stocks for the tropics, permafrost regions, wetlands, and the world. Soil 1, 351–365. https://doi.org/10.5194/soil-1-351-2015.
Kumar, A., Sharma, P., Ambrammal, S.K., 2014. Climatic effects on food grain productivity in India: a crop wise analysis. J. Stud. Dyn. Chang. 1, 38–48.
Kweku, D., Bismark, O., Maxwell, A., Desmond, K., Danso, K., Oti-Mensah, E., Quachie, A., Adormaa, B., 2018. Greenhouse effect: greenhouse gases and their impact on global warming. J. Sci. Res. Reports 17, 1–9. https://doi.org/10.9734/jsrr/2017/39630.
Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304 (80), 1623–1627. https://doi.org/10.1126/science.1097396.
Lal, R., 2015. Sequestering carbon and increasing productivity by conservation agriculture. J. Soil Water Conserv. 70, 55A–62A. https://doi.org/10.2489/jswc.70.3.55A.
Lal, R., 2016. Beyond COP21: potential and challenges of the "4 per thousand" initiative. J. Soil Water Conserv. 71, 20A–25A. https://doi.org/10.2489/jswc.71.1.20A.
Lal, R., 2019. Promoting "4 per thousand" and "adapting African agriculture" by south-south cooperation: conservation agriculture and sustainable intensification. Soil Tillage Res. 188, 27–34. https://doi.org/10.1016/j.still.2017.12.015.
Lal, R., Follett, R.F., Kimble, J.M., 2003. Achieving soil carbon sequestration in the United States: a challenge to the policy makers. Soil Sci. 168, 827–845. https://doi.org/10.1097/01.ss.0000106407.84926.6b.
Lal, R., Smith, P., Jungkunst, H.F., Mitsch, W.J., Lehmann, J., Ramachandran Nair, P.K., McBratney, A.B., De Moraes Sá, J.C., Schneider, J., Zinn, Y.L., Skorupa, A.L.A., Zhang, H.L., Minasny, B., Srinivasrao, C., Ravindranath, N.H., 2018. The carbon sequestration potential of terrestrial ecosystems. J. Soil Water Conserv. 73, 145A–152A. https://doi.org/10.2489/jswc.73.6.145A.
Landholm, D.M., Pradhan, P., Wegmann, P., Sánchez, M.A.R., Salazar, J.C.S., Kropp, J.P., 2019. Reducing deforestation and improving livestock productivity: greenhouse gas mitigation potential of silvopastoral systems in Caquetá. Environ. Res. Lett. 14, 114007. https://doi.org/10.1088/1748-9326/ab3db6.
Le Quéré, C., Andrew, R.M., Canadell, J.G., Sitch, S., Ivar Korsbakken, J., Peters, G.P., Manning, A.C., Boden, T.A., Tans, P.P., Houghton, R.A., Keeling, R.F., Alin, S., Andrews, O.D., Anthoni, P., Barbero, L., Bopp, L., Chevallier, F., Chini, L.P., Ciais, P., Currie, K., Delire, C., Doney, S.C., Friedlingstein, P., Gkritzalis, T., Harris, I., Hauck, J., Haverd, V., Hoppema, M., Klein Goldewijk, K., Jain, A.K., Kato, E., Körtzinger, A., Landschützer, P., Lefèvre, N., Lenton, A., Lienert, S., Lombardozzi, D., Melton, J.R., Metzl, N., Millero, F., Monteiro, P.M.S., Munro, D.R., Nabel, J.E.M.S., Nakaoka, S.I., O'Brien, K., Olsen, A.,

Omar, A.M., Ono, T., Pierrot, D., Poulter, B., Rödenbeck, C., Salisbury, J., Schuster, U., Schwinger, J., Séférian, R., Skjelvan, I., Stocker, B.D., Sutton, A.J., Takahashi, T., Tian, H., Tilbrook, B., Van Der Laan-Luijkx, I.T., Van Der Werf, G.R., Viovy, N., Walker, A.P., Wiltshire, A.J., Zaehle, S., 2016. Global carbon budget 2016. Earth Syst. Sci. Data 8, 605–649. https://doi.org/10.5194/essd-8-605-2016.

Leifeld, J., Ammann, C., Neftel, A., Fuhrer, J., 2011. A comparison of repeated soil inventory and carbon flux budget to detect soil carbon stock changes after conversion from cropland to grasslands. Glob. Chang. Biol. 17, 3366–3375. https://doi.org/10.1111/j.1365-2486.2011.02471.x.

Li, C., 1996. The DNDC Model, Evaluation of Soil Organic Matter Models. Springer, Berlin, pp. 263–267 https://doi.org/10.1007/978-3-642-61094-3_20.

Li, J., Yuan, X., Ge, L., Li, Q., Li, Z., Wang, L., Liu, Y., 2020. Rhizosphere effects promote soil aggregate stability and associated organic carbon sequestration in rocky areas of desertification. Agric. Ecosyst. Environ. 304, 107126. https://doi.org/10.1016/j.agee.2020.107126.

Luo, Z., Wang, E., Sun, O.J., 2010. Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. Agric. Ecosyst. Environ. 139, 224–231. https://doi.org/10.1016/j.agee.2010.08.006.

Mahanta, S.K., Ghosh, P.K., Ramakrishnan, S., 2019. Tropical grasslands as potential carbon sink. In: P., G., S., M., D., M., B., M., S., R. (Eds.), Carbon Management in Tropical and Sub-tropical Terrestrial Systems. Springer, Singapore, pp. 299–311 https://doi.org/10.1007/978-981-13-9628-1_18.

Mandal, A., Majumder, A., Dhaliwal, S.S., Toor, A.S., Mani, P.K., Naresh, R.K., Gupta, R.K., Mitran, T., 2020. Impact of agricultural management practices on soil carbon sequestration and its monitoring through simulation models and remote sensing techniques: a review. Crit. Rev. Environ. Sci. Technol. 1, 49. https://doi.org/10.1080/10643389.2020.1811590.

Marafon, G., Barbosa, R.S., de Jesus Lacerda, J.J., Martins, V., e Silva, J. de D.F., Costa, O.S., 2020. C and P pool restoration by a no-tillage system on Brazilian Cerrado Oxisol in Piauí State. Environ. Monit. Assess. 192, 254. https://doi.org/10.1007/s10661-020-8221-6.

Maraseni, T.N., Mitchell, C., 2016. An assessment of carbon sequestration potential of riparian zone of condamine catchment, Queensland, Australia. Land Use Policy 54, 139–146. https://doi.org/10.1016/j.landusepol.2016.02.013.

Martí-Roura, M., Hagedorn, F., Rovira, P., Romanyà, J., 2019. Effect of land use and carbonates on organic matter stabilization and microbial communities in Mediterranean soils. Geoderma 351, 103–115. https://doi.org/10.1016/j.geoderma.2019.05.021.

Mathew, I., Shimelis, H., Mutema, M., Chaplot, V., 2017. What crop type for atmospheric carbon sequestration: results from a global data analysis. Agric. Ecosyst. Environ. 243, 34–46. https://doi.org/10.1016/j.agee.2017.04.008.

McDaniel, M.D., Tiemann, L.K., Grandy, A.S., 2014. Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. Ecol. Appl. 24, 560–570. https://doi.org/10.1890/13-0616.1.

McSherry, M.E., Ritchie, M.E., 2013. Effects of grazing on grassland soil carbon: a global review. Glob. Chang. Biol. 19, 1347–1357. https://doi.org/10.1111/gcb.12144.

MCTI - Ministry of Science, Technology and Innovation, 2020. Report of Annual Estimates of Greenhouse Gas Emissions in Brazil. 5th edition. Ministério da Ciência, Tecnologia e Inovação, Brasília, DF http://www.brazil.gov.br/@@search?Subject%3Alist=Ministry%20of%20Science,%20Technology,%20Innovation%20and%20Communications%20(MCTIC. (Accessed 23 April 2021).

Moreira, S.L.S., Imbuzeiro, H.M.A., Silvert, C., Dietrich, O.H.S., Pimentel, L.D., Fernandes, R.B.A., 2020. Above- and below-ground carbon accumulation in cultivated macauba palm and potential to generate carbon credits. J. Clean. Prod. 265, 121628. https://doi.org/10.1016/j.jclepro.2020.121628.

Muchane, M.N., Sileshi, G.W., Gripenberg, S., Jonsson, M., Pumariño, L., Barrios, E., 2020. Agroforestry boosts soil health in the humid and sub-humid tropics: a meta-analysis. Agric. Ecosyst. Environ. 295, 106899. https://doi.org/10.1016/j.agee.2020.106899.

Narayana, J., Shashidhar, Nanda, A., Savinaya, M.S., 2020. Carbon sequestration potential of trees in Kuvempu University Campus Forest Area, Western Ghats, Karnataka. In: N., R., S., R., S., N., S., A., S., B. (Eds.), Environmental Science and Engineering. Springer, Cham, pp. 303–312 https://doi.org/10.1007/978-3-030-32463-6_15.

National Oceanic and Atmospheric Administration, Office for Coastal Management, 2020. Coastal Change Analysis 13 Program (C-CAP) Regional Land Cover. NOAA Office for Coastal Management, Charleston, SC www.coast.noaa.gov/htdata/raster1/landcover/bulkdownload/30m_lc/. (Accessed 14 December 2020).

Nayeb, H., Mirabi, M., Motiee, H., Alighardashi, A., Khoshgard, A., 2019. Estimating greenhouse gas emissions from Iran's domestic wastewater sector and modeling the emission scenarios by 2030. J. Clean. Prod. 236, 117–167. https://doi.org/10.1016/j.jclepro.2019.117673.

Ni-Meister, W., Lee, S., Strahler, A.H., Woodcock, C.E., Schaaf, C., Yao, T., Ranson, K.J., Sun, G., Blair, J.B., 2010. Assessing general relationships between aboveground biomass and vegetation structure parameters for improved carbon estimate from lidar remote sensing. J. Geophys. Res. Biogeosci. 115. https://doi.org/10.1029/2009jg000936 (n/a-n/a).

Ochieng, R.M., Visseren-Hamakers, I.J., Arts, B., Brockhaus, M., Herold, M., 2016. Institutional effectiveness of REDD+ MRV: countries progress in implementing technical guidelines and good governance requirements. Environ. Sci. Pol. 61, 42–52. https://doi.org/10.1016/j.envsci.2016.03.018.

Oelbermann, M., Voroney, R.P., 2011. An evaluation of the century model to predict soil organic carbon: examples from Costa Rica and Canada. Agrofor. Syst. 82, 37–50. https://doi.org/10.1007/s10457-010-9351-6.

Ogle, S.M., Breidt, F.J., Paustian, K., 2005. Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. Biogeochemistry 72, 87–121. https://doi.org/10.1007/s10533-004-0360-2.

Ogle, S.M., Alsaker, C., Baldock, J., Bernoux, M., Breidt, F.J., McConkey, B., Regina, K., Vazquez-Amabile, G.G., 2019. Climate and soil characteristics determine where no-till management can store carbon in soils and mitigate greenhouse gas emissions. Sci. Rep. 9, 11665. https://doi.org/10.1038/s41598-019-47861-7.

Olawuyi, S.O., 2019. Effect of adoption of alternative conservation agricultural practices on smallholder farmers' production output in South-West Nigeria. Cogent Soc. Sci. 5. https://doi.org/10.1080/23311886.2019.1588447.

Olivier, J.G.J., Peters, J.A.H.W., 2020. Trends in global CO_2 and total greenhouse gas emissions: report 2019. PBL Netherlands Environ. Assess. Agency 2020, p. 70.

Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., Hayes, D., 2011. A large and persistent carbon sink in the world's forests. Science 333 (80), 988–993. https://doi.org/10.1126/science.1201609.

Papini, R., Valboa, G., Favilli, F., L'Abate, G., 2011. Influence of land use on organic carbon pool and chemical properties of Vertic Cambisols in central and southern Italy. Agric. Ecosyst. Environ. 140, 68–79. https://doi.org/10.1016/j.agee.2010.11.013.

Parton, W.J., Stewart, J.W.B., Cole, C.V., 1988. Dynamics of C, N, P and S in grassland soils: a model. Biogeochemistry 5, 109–131. https://doi.org/10.1007/BF02180320.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.P., Smith, P., 2016. Climate-smart soils. Nature 532 (7597), 49–57. https://doi.org/10.1038/nature17174.

Paustian, K., Collier, S., Baldock, J., Burgess, R., Creque, J., DeLonge, M., Dungait, J., Ellert, B., Frank, S., Goddard, T., Govaerts, B., Grundy, M., Henning, M., Izaurralde, R.C., Madaras, M., McConkey, B., Porzig, E., Rice, C., Searle, R., Seavy, N., Skalsky, R., Mulhern, W., Jahn, M., 2019. Quantifying carbon for agricultural soil management: from the current status toward a global soil information system. Carbon Manag. 10 (6), 567–587. https://doi.org/10.1080/17583004.2019.1633231.

Peri, P.L., Banegas, N., Gasparri, I., Carranza, C.H., Rossner, B., Pastur, G.M., Cavallero, L., López, D.R., Loto, D., Fernández, P., Powel, P., Ledesma, M., Pedraza, R., Albanesi, A., Bahamonde, H., Eclesia, R.P., Piñeiro, G., 2017. Carbon sequestration in temperate silvopastoral systems, Argentina. Integrating Landscapes: Agroforestry for Biodiversity Conservation and Food Sovereignty. Springer, Cham, pp. 453–478 https://doi.org/10.1007/978-3-319-69371-2_19.

Petersen, B.M., Knudsen, M.T., Hermansen, J.E., Halberg, N., 2013. An approach to include soil carbon changes in life cycle assessments. J. Clean. Prod. 52, 217–224. https://doi.org/10.1016/j.jclepro.2013.03.007.

Petrokofsky, G., Kanamaru, H., Achard, F., Goetz, S.J., Joosten, H., Holmgren, P., Lehtonen, A., Menton, M.C., Pullin, A.S., Wattenbach, M., 2012. Comparison of methods for measuring and assessing carbon stocks and carbon stock changes in terrestrial carbon pools. How do the accuracy and precision of current methods compare? A systematic review protocol. Environ. Evid. 1 (1), 1–21. https://doi.org/10.1186/2047-2382-1-6.

Phillips, O.L., Malhi, Y., Vinceti, B., Baker, T., Lewis, S.L., Higuchi, N., Laurance, W.F., Núñez Vargas, P., Vásquez Martinez, R., Laurance, S., Ferreira, L.V., Stern, M., Brown, S., Grace, J., 2002. Changes in growth of tropical forests: evaluating potential biases. Ecol. Appl. 12, 576–587. https://doi.org/10.1890/1051-0761(2002)012[0576:CIGOTF]2.0.CO;2.

Poeplau, C., Don, A., 2015. Carbon sequestration in agricultural soils via cultivation of cover crops - a meta-analysis. Agric. Ecosyst. Environ. 200, 33–41. https://doi.org/10.1016/j.agee.2014.10.024.

Post, W.M., Izaurralde, R.C., Jastrow, J.D., McCarl, B.A., Amonette, J.E., Bailey, V.L., ... Zhou, J., 2004. Enhancement of carbon sequestration in US soils. Bioscience 54 (10), 895–908. https://doi.org/10.1641/0006-3568(2004)054[0895:EOCSIU]2.0.CO;2.

Powlson, D.S., Bhogal, A., Chambers, B.J., Coleman, K., Macdonald, A.J., Goulding, K.W.T., Whitmore, A.P., 2012. The potential to increase soil carbon stocks through reduced tillage or organic material additions in England and Wales: a case study. Agric. Ecosyst. Environ. 146, 23–33. https://doi.org/10.1016/j.agee.2011.10.004.

Powlson, D.S., Stirling, C.M., Thierfelder, C., White, R.P., Jat, M.L., 2016. Does conservation agriculture deliver climate change mitigation through soil carbon sequestration in tropical agro-ecosystems? Agric. Ecosyst. Environ. 220, 164–174. https://doi.org/10.1016/j.agee.2016.01.005.

Pu, C., Kan, Z. Rong, Liu, P., Ma, S. Tian, Qi, J. Ying, Zhao, X., Zhang, H. Lin, 2019. Residue management induced changes in soil organic carbon and total nitrogen under different tillage practices in the North China Plain. J. Integr. Agric. 18, 1337–1347. https://doi.org/10.1016/S2095-3119(18)62079-9.

Rainaudo, M., 2019. Informe de evolución de Siembra Directa en Argentina. Campaña 2018/19. Asociación Argentina de Productores en Siembra directa (AAPRESID) https://issuu.com/aapresid/docs/informe_essd_aapresid_bc_comp.

Ramachandran Nair, P.K., Nair, V.D., Mohan Kumar, B., Showalter, J.M., 2010. Carbon sequestration in agroforestry systems. Adv. Agron. 108, 237–307. https://doi.org/10.1016/S0065-2113(10)08005-3.

Ribeiro, R.H., Ibarr, M.A., Besen, M.R., Bayer, C., Piva, J.T., 2019. Managing grazing intensity to reduce the global warming potential in integrated crop–livestock systems under no-till agriculture. Eur. J. Soil Sci. 71, 1120–1131. https://doi.org/10.1111/ejss.12904.

Ricard, M.F., Viglizzo, E.F., 2020. Improving carbon sequestration estimation through accounting carbon stored in grassland soil. MethodsX 7. https://doi.org/10.1016/j.mex.2019.12.003.

Richards, G.P., 2001. The FullCAM carbon accounting model: development, calibration implementation. Strateg. 50.

Rigon, J.P.G., Franzluebbers, A.J., Calonego, J.C., 2020. Soil aggregation and potential carbon and nitrogen mineralization with cover crops under tropical no-till. J. Soil Water Conserv. 75, 601–609. https://doi.org/10.2489/jswc.2020.00188.

Rodas-Zuluaga, L.I., Castañeda-Hernández, L., Castillo-Vacas, E.I., Gradiz-Menjivar, A., López-Pacheco, I.Y., Castillo-Zacarías, C., Boully, L., Iqbal, H.M.N., Parra-Saldívar, R., 2021. Bio-capture and influence of CO_2 on the growth rate and biomass composition of the microalgae Botryococcus braunii and Scenedesmus sp. J. CO_2 Util. 43, 101371. https://doi.org/10.1016/j.jcou.2020.101371.

Rodríguez, L., Suárez, J.C., Rodriguez, W., Artunduaga, K.J., Lavelle, P., 2021. Agroforestry systems impact soil macroaggregation and enhance carbon storage in Colombian deforested Amazonia. Geoderma 384, 114810. https://doi.org/10.1016/j.geoderma.2020.114810.

Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., Handa, C., Kheshgi, H., Kobayashi, S., Kriegler, E., Mundaca, L., Séférian, R., Vilariño, M.V., 2018. Mitigation pathways compatible with 1.5°C in the context of sustainable development. Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathw. IPCC Spec. Rep. Glob. Warm. 1.5°C https://www.ipcc.ch/sr15/. (Accessed 23 April 2021) (82 pp.).

Rogge, D., Bauer, A., Zeidler, J., Mueller, A., Esch, T., Heiden, U., 2018. Building an exposed soil composite processor (SCMaP) for mapping spatial and temporal characteristics of soils with Landsat imagery (1984–2014). Remote Sens. Environ. 205, 1–17. https://doi.org/10.1016/j.rse.2017.11.004.

Rumpel, C., Amiraslani, F., Chenu, C., Garcia Cardenas, M., Kaonga, M., Koutika, L.S., Ladha, J., Madari, B., Shirato, Y., Smith, P., Soudi, B., Soussana, J.F., Whitehead, D., Wollenberg, E., 2020. The 4p1000 initiative: opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy. Ambio 49, 350–360. https://doi.org/10.1007/s13280-019-01165-2.

Sá, J.C. de M., Lal, R., Cerri, C.C., Lorenz, K., Hungria, M., de Faccio Carvalho, P.C., 2017. Low-carbon agriculture in South America to mitigate global climate change and advance food security. Environ. Int. 98, 102–112. https://doi.org/10.1016/j.envint.2016.10.020.

Saha, D., Kukal, S.S., 2015. Soil structural stability and water retention characteristics under different land uses of degraded lower himalayas of North-West India. L. Degrad. Dev. 26, 263–271. https://doi.org/10.1002/ldr.2204.

Salton, J.C., Mercante, F.M., Tomazi, M., Zanatta, J.A., Concenço, G., Silva, W.M., Retore, M., 2014. Integrated crop-livestock system in tropical Brazil: toward a sustainable production system. Agric. Ecosyst. Environ. 190, 70–79. https://doi.org/10.1016/j.agee.2013.09.023.

Sanderman, J., Hengl, T., Fiske, G.J., 2017. Soil carbon debt of 12,000 years of human land use. Proc. Natl. Acad. Sci. U. S. A. 114, 9575–9580. https://doi.org/10.1073/pnas.1706103114.

Scholes, M.C., Scholes, R.J., 2013. Dust unto dust. Science 342 (6158), 565–566. https://doi.org/10.1126/science.1244579.

Schulp, C.J.E., Nabuurs, G.J., Verburg, P.H., 2008. Future carbon sequestration in Europe-effects of land use change. Agric. Ecosyst. Environ. 127, 251–264. https://doi.org/10.1016/j.agee.2008.04.010.

Simonson, W., Ruiz-Benito, P., Valladares, F., Coomes, D., 2016. Modelling above-ground carbon dynamics using multi-temporal airborne lidar: insights from a Mediterranean woodland. Biogeosciences 13, 961–973. https://doi.org/10.5194/bg-13-961-2016.

Singh, V., Tewari, A., Kushwaha, S.P.S., Dadhwal, V.K., 2011. Formulating allometric equations for estimating biomass and carbon stock in small diameter trees. For. Ecol. Manag. 261, 1945–1949. https://doi.org/10.1016/j.foreco.2011.02.019.

Smith, P., Smith, J.U., Powlson, D.S., McGill, W.B., Arah, J.R.M., Chertov, O.G., Coleman, K., Franko, U., Frolking, S., Jenkinson, D.S., Jensen, L.S., Kelly, R.H., Klein-Gunnewiek, H., Komarov, A.S., Li, C., Molina, J.A.E., Mueller, T., Parton, W.J., Thornley, J.H.M., Whitmore, A.P., 1997. A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. Geoderma 81, 153–225. https://doi.org/10.1016/S0016-7061(97)00087-6.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., Smith, J., 2008. Greenhouse gas mitigation in agriculture. Philos. Trans. R. Soc. B Biol. 363 (1492), 789–813. https://doi.org/10.1098/rstb.2007.2184.

Smith, W.N., Grant, B.B., Desjardins, R.L., Qian, B., Hutchinson, J., Gameda, S., 2009. Potential impact of climate change on carbon in agricultural soils in Canada 2000–2099. Clim. Chang. 93, 319–333. https://doi.org/10.1007/s10584-008-9493-y.

Smith, P., Soussana, J.F., Angers, D., Schipper, L., Chenu, C., Rasse, D.P., Batjes, N.H., van Egmond, F., McNeill, S., Kuhnert, M., Arias-Navarro, C., Olesen, J.E., Chirinda, N., Fornara, D., Wollenberg, E., Álvaro-Fuentes, J., Sanz-Cobena, A., Klumpp, K., 2020. How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. Glob. Chang. Biol. 26 (1), 219–241. https://doi.org/10.1111/gcb.14815.

Soussana, J.F., Lutfalla, S., Ehrhardt, F., Rosenstock, T., Lamanna, C., Havlík, P., Richards, M., Wollenberg, E. (Lini), Chotte, J.L., Torquebiau, E., Ciais, P., Smith, P., Lal, R., 2019. Matching policy and science: rationale for the '4 per 1000 - soils for food security and climate' initiative. Soil Tillage Res. 188, 3–15. https://doi.org/10.1016/j.still.2017.12.002.

Sparrevik, M., Utstøl, S., 2020. Assessing life cycle greenhouse gas emissions in the Norwegian defence sector for climate change mitigation. J. Clean. Prod. 248, 119196. https://doi.org/10.1016/j.jclepro.2019.119196.

Stern, N., 2007. The Economics of Climate Change: The Stern Review, The Economics of Climate Change: The Stern Review. Cambridge University Press https://doi.org/10.1017/CBO9780511817434.

Stevens, A., van Wesemael, B., Vandenschrick, G., Touré, S., Tychon, B., 2006. Detection of carbon stock change in agricultural soils using spectroscopic techniques. Soil Sci. Soc. Am. J. 70, 844–850. https://doi.org/10.2136/sssaj2005.0025.

Stevens, A., van Wesemael, B., Bartholomeus, H., Rosillon, D., Tychon, B., Ben-Dor, E., 2008. Laboratory, field and airborne spectroscopy for monitoring organic carbon content in agricultural soils. Geoderma 144, 395–404. https://doi.org/10.1016/j.geoderma.2007.12.009.

Stockmann, U., Adams, M.A., Crawford, J.W., Field, D.J., Henakaarchchi, N., Jenkins, M., Minasny, B., McBratney, A.B., Courcelles, V. de R. de, Singh, K., Wheeler, I., Abbott, L., Angers, D.A., Baldock, J., Bird, M., Brookes, P.C., Chenu, C., Jastrow, J.D., Lal, R., Lehmann, J., O'Donnell, A.G., Parton, W.J., Whitehead, D., Zimmermann, M., 2013. The knowns, known unknowns and unknowns of sequestration of soil organic carbon. Agric. Ecosyst. Environ. 164, 80–99. https://doi.org/10.1016/j.agee.2012.10.001.

Stolbovoy, V., Montanarella, L., Filippi, N., Jones, A., Gallego, J., Grassi, G., 2007. Soil Sampling Protocol to Certify the Changes of Organic Carbon Stock in Mineral Soil of the European Union. Version 2. EUR 21576 EN/2. Office for Official Publications of the European Communities, Luxembourg (ISBN: 978-92-79-05379-5. 56 pp.).

Taboada, Peralta, 2020. Conociendo la huella de carbono de rotaciones en siembra directa (unpublished). Presentation. https://www.aapresid.org.ar/sistemachacras/conociendo-la-huella-de-carbono-de-rotaciones-en-siembra-directa/. (Accessed 23 April 2021).

Taghizadeh-Toosi, A., Christensen, B.T., Hutchings, N.J., Vejlin, J., Kätterer, T., Glendining, M., Olesen, J.E., 2014. C-TOOL: a simple model for simulating whole-profile carbon storage in temperate agricultural soils. Ecol. Model. 292, 11–25. https://doi.org/10.1016/j.ecolmodel.2014.08.016.

Tang, L., Ke, X., Zhou, Q., Wang, L., Koomen, E., 2020. Projecting future impacts of cropland reclamation policies on carbon storage. Ecol. Indic. 119, 106835. https://doi.org/10.1016/j.ecolind.2020.106835.

Taylor, A.M., Amiro, B.D., Fraser, T.J., 2013. Net CO_2 exchange and carbon budgets of a three-year crop rotation following conversion of perennial lands to annual cropping in Manitoba, Canada. Agric. For. Meteorol. 182–183, 67–75. https://doi.org/10.1016/j.agrformet.2013.07.008.

Teague, W.R., Apfelbaum, S., Lal, R., Kreuter, U.P., Rowntree, J., Davies, C.A., Conser, R., Rasmussen, M., Hatfeld, J., Wang, T., Wang, F., Byck, P., 2016. The role of ruminants in reducing agriculture's carbon footprint in North America. J. Soil Water Conserv. 71 (2), 156–164. https://doi.org/10.2489/jswc.71.2.156.

Terrer, C., Phillips, R., Hungate, B., Rosende, J., Pett-Ridge, J., Craig, M., van Groenigen, K., Keenan, T., Sulman, B., Stocker, B., Reich, P., Pellegrini, A., Pendall, E., Zhang, H., Evans, R., Carrillo, Y., Fisher, J., Van Sundert, K., Vicca, S., Jackson, R., 2021. A trade-off between plant and soil carbon storage under elevated CO_2. Nature 591, 599–603. https://doi.org/10.1038/s41586-021-03306-8.

Tett, S.F.B., Betts, R., Crowley, T.J., Gregory, J., Johns, T.C., Jones, A., Osborn, T.J., Österom, E., Roberts, D.L., Woodage, M.J., 2007. The impact of natural and anthropogenic forcings on climate and hydrology since 1550. Clim. Dyn. 28, 3–34. https://doi.org/10.1007/s00382-006-0165-1.

Thamo, T., Pannell, D.J., 2016. Challenges in developing effective policy for soil carbon sequestration: perspectives on additionality, leakage, and permanence. Clim. Pol. 16, 973–992. https://doi.org/10.1080/14693062.2015.1075372.

Tubiello, F.N., Salvatore, M., Cóndor Golec, R.D., Ferrara, A., Rossi, S., Biancalani, R., Federici, S., Jacobs, H., Flammini, A., 2014. Agriculture, forestry and other land use emissions by sources and removals by sinks. ESS Working Paper No.2 https://doi.org/10.13140/2.1.4143.4245.

UNEP, 2019. Emissions gap report 2019 executive summary. Emiss. Gap Rep. 2019 , p. 82. https://unepdtu.org/publications/emissions-gap-report-2019-executivesummary/#:~:text=The%20UNEP%20Emissions%20Gap%20Report,3.2%C2%B0C%20temperature%20rise. (Accessed 23 April 2021).

United Nations., 2020. (accessed April 23, 2021) unstats.un.org/sdgs/report/2020/The-Sustainable-Development-Goals-Report-2020.pdf

Ussiri, D.A.N., Lal, R., 2009. Long-term tillage effects on soil carbon storage and carbon dioxide emissions in continuous corn cropping system from an alfisol in Ohio. Soil Tillage Res. 104, 39–47. https://doi.org/10.1016/j.still.2008.11.008.

Valkama, E., Kunypiyaeva, G., Zhapayev, R., Karabayev, M., Zhusupbekov, E., Perego, A., Schillaci, C., Sacco, D., Moretti, B., Grignani, C., Acutis, M., 2020. Can conservation agriculture increase soil carbon sequestration? A modelling approach. Geoderma 369, 114298. https://doi.org/10.1016/j.geoderma.2020.114298.

Van den Broeck, G., Grovas, R.R.P., Maertens, M., Deckers, J., Verhulst, N., Govaerts, B., 2013. Adoption of conservation agriculture in the Mexican Bajío. Outlook Agric. 42, 171–178. https://doi.org/10.5367/oa.2013.0136.

Vicente-Vicente, J.L., García-Ruiz, R., Francaviglia, R., Aguilera, E., Smith, P., 2016. Soil carbon sequestration rates under Mediterranean woody crops using recommended management practices: a meta-analysis. Agric. Ecosyst. Environ. 235, 204–214. https://doi.org/10.1016/j.agee.2016.10.024.

Viglizzo, E.F., Taboad, M.A., Vázquez-Amábile, G., Ricard, M.F., 2020. Response to the letter to the editor the role of south American grazing lands in mitigating greenhouse gas emissions. A reply to: 'reassessing the role of grazing lands in carbon-balance estima- tions: meta-analysis and review'. Sci. Total Environ. 740, 140119 (doi: 10.1016/j.scitotenv.2020.1401 19 PII: S0048-9697(20)33640-8).

Villarino, S.H., Pinto, P., Chiesa, T.D., Jobbágy, E.G., Studdert, G.A., Bazzoni, B., Conti, G., Rufino, M., Álvarez, R., Boddey, R., Bayer, C., Carvalho, P.C.F., Fernández, R.J., Lattanzi, F.A., Oesterheld, M., Oyhantçabal, W., Paruelo, J.M., Pravia, V., Piñeiro, G., 2020. The role of south American grazing lands in mitigating greenhouse gas emissions. A reply to:"reassessing the role of grazing lands incarbon-balance estimations: meta-analysis and review", by Viglizzo et al., 2019. Sci. Total Environ. 740, 140108. https://doi.org/10.1016/j.scitotenv.2020.140108.

Vleeshouwers, L.M., Verghagen, A., 2002. Carbon emission and sequestration by agricultural land use: a model study for Europe. Glob. Chang. Biol. 8, 519–530. https://doi.org/10.1046/j.1365-2486.2002.00485.x.

Wang, X., Jing, Z.H., He, C., Liu, Q.Y., Qi, J.Y., Zhao, X., Xiao, X.P., Zhang, H.L., 2021. Temporal variation of SOC storage and crop yield and its relationship - a fourteen year field trial about tillage practices in a double paddy cropping system, China. Sci. Total Environ. 759. https://doi.org/10.1016/j.scitotenv.2020.143494.

Wanner, H., Beer, J., Bütikofer, J., Crowley, T.J., Cubasch, U., Flückiger, J., Goosse, H., Grosjean, M., Joos, F., Kaplan, J.O., Küttel, M., Müller, S.A., Prentice, I.C., Solomina, O., Stocker, T.F., Tarasov, P., Wagner, M., Widmann, M., 2008. Mid- to Late Holocene climate change: an overview. Quat. Sci. Rev. 27, 1791–1828. https://doi.org/10.1016/j.quascirev.2008.06.013.

Watts, J.D., Lawrence, R.L., Miller, P.R., Montagne, C., 2009. Monitoring of cropland practices for carbon sequestration purposes in north central Montana by Landsat remote sensing. Remote Sens. Environ. 113, 1843–1852. https://doi.org/10.1016/j.rse.2009.04.015.

West, P.C., Gibbs, H.K., Monfreda, C., Wagner, J., Barford, C.C., Carpenter, S.R., Foley, J.A., 2010. Trading carbon for food: global comparison of carbon stocks vs. crop yields on agricultural land. Proc. Natl. Acad. Sci. U. S. A. 107, 19645–19648. https://doi.org/10.1073/pnas.1011078107.

Wiesmeier, M., Mayer, S., Burmeister, J., Hübner, R., Kögel-Knabner, I., 2020. Feasibility of the 4 per 1000 initiative in Bavaria: a reality check of agricultural soil management and carbon sequestration scenarios. Geoderma 369. https://doi.org/10.1016/j.geoderma.2020.114333.

World Bank, 2020. World development indicators database archives. https://databank.worldbank.org/data/download/GDP.pdf. (Accessed 13 March 2021).

Zhao, Y., Wang, M., Hu, S., Zhang, X., Ouyang, Z., Zhang, G., Huang, B., Zhao, S., Wu, J., Xie, D., Zhu, B., Yu, D., Pan, X., Xu, S., Shi, X., 2018. Economics- and policy-driven organic carbon input enhancement dominates soil organic carbon accumulation in Chinese croplands. Proc. Natl. Acad. Sci. U. S. A. 115, 4045–4050. https://doi.org/10.1073/pnas.1700292114.

Zheng, X., Streimikiene, D., Balezentis, T., Mardani, A., Cavallaro, F., Liao, H., 2019. A review of greenhouse gas emission profiles, dynamics, and climate change mitigation efforts across the key climate change players. J. Clean. Prod. 234, 1113–1133. https://doi.org/10.1016/j.jclepro.2019.06.140.

Zhong, Z., Han, X., Xu, Y., Zhang, W., Fu, S., Liu, W., Ren, C., Yang, G., Ren, G., 2019. Effects of land use change on organic carbon dynamics associated with soil aggregate fractions on the Loess Plateau, China. L. Degrad. Dev. 30, 1070–1082. https://doi.org/10.1002/ldr.3294.

A method for assessing carbon stocks, carbon sequestration, and greenhouse-gas fluxes in ecosystems of the United States under present conditions and future scenarios scientific investigations report 2010 – 5233. In: Zhu, Z. (Ed.), Carbon N. Y (188 pp.).

Zomer, R., Bossio, D., Sommer, R., Verchot, L., 2013. Geospatial estimation of the sequestration potential of increasing soil organic carbon on agricultural land. Agric. Ecosyst. Environ. 126, 67–80.

Zomer, R.J., Neufeldt, H., Xu, J., Ahrends, A., Bossio, D., Trabucco, A., Van Noordwijk, M., Wang, M., 2016. Global tree cover and biomass carbon on agricultural land: the contribution of agroforestry to global and national carbon budgets. Sci. Rep. 6, 1–12. https://doi.org/10.1038/srep29987.

Zomer, R.J., Bossio, D.A., Sommer, R., Verchot, L.V., 2017. Global sequestration potential of increased organic carbon in cropland soils. Sci. Rep. 7, 15554. https://doi.org/10.1038/s41598-017-15794-8.

Zuidema, P.A., Baker, P.J., Groenendijk, P., Schippers, P., van der Sleen, P., Vlam, M., Sterck, F., 2013. Tropical forests and global change: filling knowledge gaps. Trends Plant Sci. 18 (8), 413–419. https://doi.org/10.1016/j.tplants.2013.05.006.