Catena 252 (2025) 108805

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Assessment of soil integration in nationally determined contributions and guidance for quantifying ex-ante soil organic carbon stock changes in national policies using IPCC default methodologies☆

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ARTICLE INFO

Keywords:
Carbon stocks
GHG emissions
Soil
Nationally determined contribution
National greenhouse gas inventories

ABSTRACT

By 2025, Parties will have to submit to the United Nations Framework Convention on Climate Change (UNFCCC) a new or updated nationally determined contribution (NDC), with more ambitious climate commitments as compared to the previous one. It is thus expected that Parties will raise their ambition regarding their actions on GHG emissions reductions and carbon removals, which in the land sector focus on the living biomass, dead organic matter and soil organic matter pools. This study aimed at understanding how soils and their management practices are integrated into the current NDCs, and how this information might be used to quantify ex-ante climate change mitigation potential. This study found that while some actions provide sufficient level of information to quantify their climate change mitigation potential using the IPCC tier 1 methodologies, thus default carbon stocks values (biomass and soil), few Parties actually included this data in their NDCs. However, this study provided examples of such tier 1 quantification using the Nationally Determined Contribution Expert tool (NEXT) in ex-ante analyses. This type of ex-ante analyses is considered to be a starting point for discussions and collaboration between policy makers and technical experts involved in formulating NDCs and developing national greenhouse gas inventories. These analyses are also essential for improving data collection, increasing accuracy (thus decreasing uncertainties), strengthening credibility and feasibility, and paving the way for enhancing environmental ambitions and building countries' capacities.

1. Introduction

The Paris Agreement (PA) enabled an international consensus to be reached to limit the increase of global temperatures to 1.5 °C above pre-industrial level. This requires avoiding, reducing and offsetting greenhouse gas (GHG) emissions. Agricultural soil can play an important role in this, and it was already recognized in Article 3.4 of the Kyoto Protocol "[..] The Conference of the Parties serving as the meeting of the Parties to this Protocol shall, at its first session or as soon as practicable thereafter, decide upon modalities, rules and guidelines as to how, and which, additional human-induced activities related to changes in greenhouse gas emissions by sources and removals by sinks in the agricultural soils and the land-use change and forestry categories shall be added to, or subtracted from, the assigned amounts for Parties included in Annex I […]", (UNFCCC, 2024a). While discussions within the scientific community remain ongoing with regards to soil organic carbon (SOC) sequestration potential (Minasny et al, 2017; van Groeningen et al., 2017; Soussana et al., 2017; Rumpel et al., 2018; de Vries 2018; White et al., 2018; Minasny et al., 2018; Soussana et al., 2019; Rumpel et al., 2020; Janzen et al., 2022, Minasny et al., 2023), numerous international initiatives have still emerged to underscore the importance of soil in climate mitigation and adaptation policy development. For example, from the 131 countries that committed to the land degradation neutrality (LDN), 100 of them formulated national targets (UNCCD, 2024a). In the 4 per 1000 initiative, stakeholders commit to a voluntary action plan to implement agricultural practices that maintain or improve

☆ This article is part of a special issue entitled: 'Carbon inventories in agriculture and forestry' published in Catena.

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https://doi.org/10.1016/j.catena.2025.108805
Received 22 April 2024; Received in revised form 6 December 2024; Accepted 4 February 2025
Available online 19 February 2025

SOC stocks in agricultural soils and to preserve carbon-rich soils (the 4 per 1000, 2024). The new four-year Sharm el-Sheikh joint work, which builds on the outcomes of the Koronivia Joint Work on Agriculture (KJWA), aims to provide countries with technical support, expert knowledge and capacity strengthening to adapt to and mitigate climate change, (UNFCCC, 2024b; FAO, 2024a). The sustainable development goals (SDG) contain 4 targets specifically related to soils: 2.4; 3.9; 12.4 and most importantly target 15.3 which addresses soil degradation by promoting sustainable soil management (SSM) practices, (UN, 2024). The Kunming-Montreal Global Biodiversity Framework also set targets related to agriculture and soil (target 10), (CBD, 2022). The Global Soil Partnership and its RECSOIL are two mechanisms to position soils in the Global Agenda, to promote SSM, to re-carbonize the global agricultural soils and improve soil health (FAO, 2024b,c). Finally, the booming of soil carbon standards (Bispo et al., 2017) and regional and local initiatives like the soil carbon international research consortium (INRAE, 2023), ORCaSa (Orcasa, 2024), and the soil deal for Europe (European Commission, 2024), are other examples that recognize the potential of soil in combating land degradation, while contributing to numerous ecosystems services, like cleaning water, habitats for biodiversity, food security while providing climate resilience.

The last edition of the emission gap report showed that if all new and updated unconditional NDCs are fully implemented, there still remains an emissions gap from the 1.5 °C target of about 22 giga tonne of carbon dioxide equivalent ($GtCO_2$-eq) by 2030 (UNEP, 2024). In consequence, global GHG emissions should be reduced by 42 percent compared with current policy projections (UNEP, 2024). The agriculture, forestry and other land use (AFOLU) sector can play a key role in reducing GHG emissions and enhancing carbon removal, including through SOC sequestration. The sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC) estimated the mitigation potential of the AFOLU sector between 8 and 14 $GtCO_2$-eq per year at a cost below 100 USD/tCO_2-eq. The largest share of this economic potential comes from the conservation, improved management and restoration of forest and ecosystems, where soil is an important component including in coastal wetlands, peatlands, savannas and grasslands. Improved and sustainable crops and livestock management, soil carbon management in croplands and grasslands, agroforestry and biochar can contribute between 1.8 and 4.1 $GtCO_2$-eq per year (IPCC, 2022). The inclusion of soils in NDCs, LDN and Biodiversity targets have already been studied (Rose et al., 2020; Wiese et al., 2021, Wiese-Rozanova et al., 2021; Wiese-Rozanova 2022). While the share of countries explicitly referring to SOC in their NDC is increasing over time, many still face challenges related to the monitoring, estimating, reporting and verifying SOC-based NDC actions (Wiese et al., 2021). Moreover, despite the growing global support for capacity building to improve soil management, the estimation and reporting of GHG emissions and removals from mineral soils in NGHGI is also still limited, especially for developing countries which find challenges in reporting carbon stock changes (CSCs) and associated CO_2 emissions or removals from mineral soils, even when applying the basic IPCC Tier 1 methodology. In fact, when the Food and Agriculture Organization of the United Nations (FAO) and the Institute for Global Environmental Strategies (IGES) carried out a survey to understand the challenges associated with the estimation of CSCs in the national greenhouse gas inventories (NGHGI), a third of developing countries responding to it, reported CSCs in mineral soils in their GHGI. The lack of activity data on land management and soil-specific data where identified as the main challenges (FAO & IGES, 2022). Other challenges included the lack of soil-/land-use-specific data, limited resources (human, infrastructure for data collection), limited knowledge, even difficulty in understanding the IPCC methodologies. It is also worth noting from the same survey that the majority of developing countries (74 %) that included the SOC pool in their NGHGI applied the basic IPCC tier 1 methodology, using default parameters, reported estimates with high uncertainties, whereas only 26 % of the countries applied higher tier methods.

This study builds on the methodology used in the previous studies on the topic (Rose et al., 2020; Wiese et al., 2021; Wiese-Rozanova et al., 2021), and aims at understanding how soils, defined as a distinct carbon pool within the IPCC guidelines for NGHGI, and their management practices, are integrated into the NDC. This study also explores how ex-ante GHG emissions/removals from this carbon pool could be quantified based on a minimum set of information using the tier 1 methodological level as provided by IPCC to estimate SOC changes, (IPCC, 2006). For this purpose, the study covers the analysis of the formulation of the mitigation and adaptation actions related to soils, their targets, and other relevant information included in the NDCs needed to facilitate the GHG emissions/removals estimation using the simplest tier 1 approach, following the 2006 IPCC guidelines (IPCC, 2006) in an effort to demonstrate opportunities for inclusion or enhancement in the next round of NDCs. The findings also illustrate areas for the future improvement of data and methodology on soil.

2. Material and methods

This research is based on an analysis of mitigation and adaptation actions related to soils included in the latest NDCs submitted to the UNFCCC as of 31 December 2023,[1] representing 167 Parties to the UNFCCC (166 country Parties and the European Union). The data source is a FAO database, which was developed based on a screening of all NDC documents against the FAO protocol for NDC data analysis and extraction for agrifood systems (Crumpler et al., 2024). Based on the FAO protocol, "actions" are defined as statement tagged as "option", "activity", "measure" or "intervention" and are explicitly articulated as a strategy to implement the mitigation or adaptation component of the NDC. The definition of action also includes "project", "programme", "initiative", "policy", "strategy", "contribution", "commitment", "effort", "priority". Thus, some NDCs might have included an adaptation or mitigation "goal" or "objective" (e.g. achieve a net zero and climate-resilient future) but do not include concrete actions (e.g. zero tillage), such as Niue, Singapore and Ukraine. Our soil-related keywords list was derived from Wiese et al., 2021 and supplemented with new entries, Table 1 in the supplementary material. As the occurrence of keywords related to SOC returned only 34 Parties proposing 69 mitigation actions, Fig. 1, the search was therefore extended to keywords associated with SSM practices, as described in the Voluntary guideline for soil management (FAO, 2017a) and IPCC methodologies (IPCC, 2006 and IPCC, 2019), for which the action would support the enhancement, protection or conservation of SOC. A third screening included land uses for which soil is a dominant component in carbon stock changes estimation, such as grassland, savanna, mangroves, seagrass, and peatland, among others, Table 1 in the supplementary material. For example, the action "Protection and restoration of grassland ecosystems will also be strengthened, so as the protection of wetlands" does not make explicit reference to soil and associated management practices, but it still suggests that SOC stock might be preserved and enhanced in the case of grassland. The same applies to the action "The average annual rate of loss of natural grasslands for the 2026–2030 period is 50 % (0.685 % average annual rate for the 2026–2030 period) compared to that of the 2000–2015 period at the national level (1.37 %)" which also includes a target for quantifying the SOC loss avoided. Results from the three screenings were finally summed into a broader category "soil total" from which the mitigation and adaptation analyses started. Following this, actions were also screened according to the land-use categories they refer to as described in the IPCC guidelines for NGHGI, i.e. forest land, cropland, grassland, and wetlands, Table 2 in the supplementary material. After filtering, actions were read individually to add or remove any actions that should have been labelled or not under one of the above

[1] Except for Brazil, for which we used the two last NDCs for adaptation actions and the last NDC for mitigation actions.

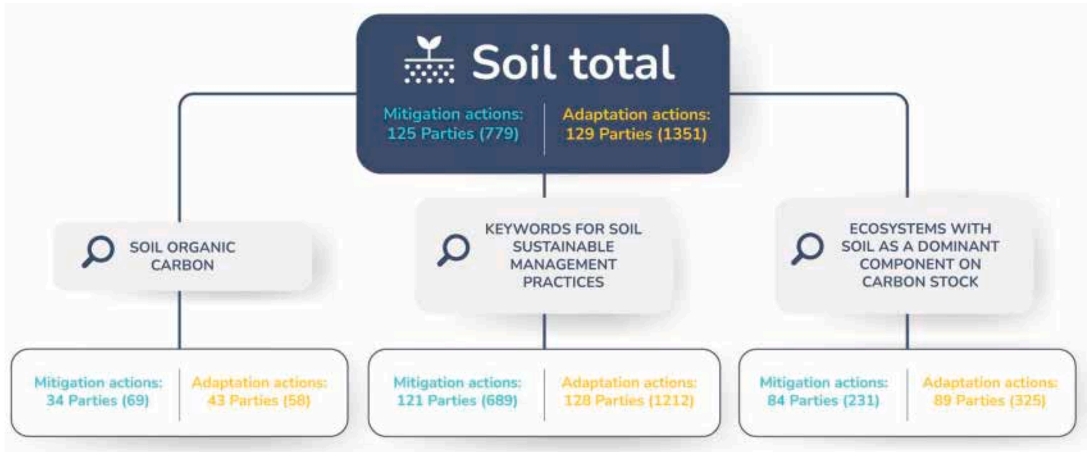

Fig. 1. Description of the three screening processes used to retrieve soil-related actions in the mitigation and adaptation components of the NDC database.

categories.

Sustainable soil management practices were also disaggregated into different variables to understand the main topics and management practices associated to cropland, grassland, forest land and wetlands, Table 1. All keywords were screened across all land uses, with some exceptions as described hereafter. Residues management keywords were not applied to forest to avoid counting actions associated with fire in forest. This is the same for "other forest" to avoid double counting with fire mentioned in cropland. The keyword fire was used for all actions excluding those related to cropland. For forest, if an action returned a positive result for keywords related to afforestation or deforestation, the "other forest" entry was zeroed to avoid any double accounting. For the keyword "planting" we associated a condition related to the land use, i.e. cropland and forest land. If planting was associated to cropland, it returned 1 under agroforestry but 0 under "afforestation". If planting was associated to forest, it returned 1 under "afforestation" but 0 under cropland.

A last screening was carried out to analyze if actions include a GHG (e.g. "20 % reduction in CO2eq by 2040 compared to 2010 level") and or a non GHG target (eg. afforest 100 ha of land). A search function with keywords "hectares", "ha", "%", "percent", "CO2", "USD", "US$", "farmer", and "tree" was performed, which provided indication of the range and sufficiency of information included that could be used to conduct an ex-ante climate change mitigation analysis.

3. Results

Out of the 167 NDC submissions reviewed, a total of 1,284 actions under the mitigation section and 5,228 under the adaptation section were extracted in relation to the AFOLU sector and agrifood systems (including Energy, Waste, and Industrial processes and product use IPCC sectors). Out of those, a total of 125 Parties reported 781 mitigation actions (61 % of all mitigation actions), and 129 Parties reported 1,351 adaptation actions (26 % of all adaptation actions) related to soil (as SOC, soil land use and SSM). Among all the submissions, 11 Parties did not include any soil-related action in their NDC, 24 Parties included soil-related actions only in their adaptation component, while 20 Parties included soil-related actions only in their mitigation component.

Mitigation actions: The analysis looked at the actions per region to highlight common soil measures (as SOC, soil land use and SSM) and differences between region. The countries have been grouped by region, which include the member countries of the FAO's regional offices. Soil measures (as SOC, soil land use and SSM) were found predominantly in forest land (421), followed by cropland (266), wetlands (87) and grassland (70) categories, Table 3 of the supplementary material. Soil measures could address one or more land uses, for example "[…] to restore and enhance wetlands, peatlands, grasslands and agricultural lands, as well as to improve land management practices, and conserve carbon-rich ecosystems". In that case, cropland, grassland and wetlands are the targeted land uses, with the main SSMs as grassland management, combatting land degradation and sustainable management. Overall, forest management (including afforestation and deforestation), combatting land degradation, sustainable management, agroforestry and integrated soil fertility management (ISFM) were the main topics across all regions but with some differences in intensity and between land uses (Table 1 and Fig. 2). Fig. 3 illustrates the regional distribution of SSM management practices per land use, i.e. SSM specific to cropland, or grassland, or forest land or wetlands only. For instances, in croplands, combatting land degradation, agroforestry, ISFM and climate-smart practices were the most frequent topics reported, while in wetlands, most of the actions referred to data enhancement and land degradation (restoration/conservation of mangroves or wetlands among others). The patterns between practices and land uses also differ between regions, except for forest land. In the Africa region, a wide range of SSM practices for cropland were identified compared to other regions, such as ISFM, agroforestry, land degradation, conservation agriculture, residue management, irrigation, Fig. 3. In the LAC region, Parties focused more on ISFM, climate smart practices and agroforestry for cropland management. In the other regions fewer measures for all land uses were identified. Wetlands were not covered by Parties from North America and Europe and Central Asia but were mostly reported by the LAC Parties, Fig. 3.

Adaptation actions: More actions were reported in the adaptation component of the NDC compared to the number of mitigation actions, namely 1351 against 778 actions, respectively, Table 1 of the supplementary material. For example, Africa and Europe and Central Asia regions reported almost double the number of adaptation actions compared to mitigation. The NENA region has almost three times more adaptation actions than mitigation ones. On average reporting countries mentioned 10 actions related to soil in the adaptation component against 6 in the mitigation component, Table 3 of the supplementary material. Soil measures (as SOC, soil land use and SSM) were found predominantly associated with forest land (524), followed by cropland (396), wetland (184) and grassland (97). Some of these measures also reported a climate change mitigation co-benefit, i.e. 281. Only 43 Parties reported 58 actions explicitly mentioning SOC, either for no specific land use or at least one or more together: no specific land use (30) cropland (21), grassland (2), forest (7) and wetland (2).

The distribution of SSM practices, Table 1, showed that forest management (including afforestation and reducing deforestation), combatting land degradation, sustainable management, agroforestry and ISFM were the main practices across all regions (Fig. 2), but with different

Table 1
Keywords associated with sustainable soil management practices, and occurrence of the mitigation and adaptation actions.

Sustainable management practices	Keywords used for screening	Mitigation	Adaptation
Sustainable management	sustainable management, sustainable grassland management, sustainable forest management, improv*	155	248
Combatting land degradation	Erosion, erosive, eroded Regenerated, regenerative, rehabilitated, rehabilitation, rehabilitating, degradation, degraded, erosion, shelterbelt, restoration, restored, desertification, drought	206	350
Forest management	**Afforestation:** Afforestation, afforested, reforestation, reforested, forest regeneration, planting	107	85
	Deforestation: Deforestation, deforested	67	34
	Other forest: forest, forests, tree, plantation, redd, fire, fuelwood, reserve	214	318
Data enhancement	Metrics, inventories, inventory, methodology, Samples, monitoring, quantify, MRV, standards, map, data management, research, monitored, redd, collection, collected	85	101
Conservation agriculture	**Conservation agriculture:** conservation agriculture, species diversification, legume, leguminous	10	14
	Zero-tillage: Tillage, till, no-till	11	9
	cover crop, green manure, catch crop, groundcover	5	2
	Crop rotation	14	7
	Fallow: improved fallow, fallow	2	1
Climate smart agriculture	CSA, climate smart, climate-smart, re-carbonization, recarbonisation, recarbonization, agroecology, agro-ecolog, contour, terrace, precision agriculture, yield, decarbonisation, low-carbon, decarbonization	65	138
Integrated soil fertility management (ISFM)	integrated soil fertility management, integrated soil management	0	6
	Organic amendment: Manure, compost, sludge, biochar, dung, mulch, organic	53	39
	Fertilizer, fertilizer, N2O, nitrogen, nitrous oxide, nutrient	67	34
Grassland management	Grazing, rotation, forage	25	30
Residue management	Residue, burn, burning, slash, fire, straw, residue retention	17	5
Agroforestry	Planting, agro-forestry, agroforestry, tree, shelterbelt, agri-silviculture, boundary plant, intercropping tree, perennial, orchard, plantation, cashew, coffee, cocoa, shaded	104	151
Water table management	Drainage, drained, rewetting, SRI, AWD, rice flooding, intermittent aeration, CH4, methane, reduction of emissions in rice cultivation, water withdrawal, water management practice	23	20
Irrigation	Irrigation, fertigation, irrigated	30	169

pattern between land uses. In croplands, climate smart practices, sustainable management, agroforestry and irrigation are the dominant practices reported, in particular in the Africa region, Fig. 3. In grasslands, the pattern is similar than the one for the mitigation actions, with sustainable management, grassland management and land degradation. Forest management, i.e. all activities other than afforestation/reforestation and reducing deforestation is by far the most mentioned practice in forest land across all regions, while land degradation is for wetlands. The patterns between practices and land uses also differ between regions. For example, Africa showed a wide range of practices compared to other regions, such as CSA, sustainable management and irrigation practices, in particular for croplands. Grasslands and forests were not addressed by the North America region in their adaptation actions, but only in the mitigation actions. Grassland was more represented by the Africa region, with activities related to grazing and rotation, while the NENA region focused on sustainable management.

A comparison between mitigation and adaptation actions showed that combatting land degradation, implementing forest management (including afforestation) and agroforestry were the practices most frequently mentioned in the context of both mitigation and adaptation. Irrigation and erosion control are the two others top ten categories for adaptation, while deforestation and fertilizers are the two others top ten categories for mitigation, Table 1. The sustainable management category was created as some actions do mention this, although it does not provide by itself any specific indication of the soil management practices. In the mitigation and adaptation component of the NDC it was mentioned 155 and 248 times, respectively. While it was associated with other SSM practices, this was not the case for 20 mitigation actions and 69 adaptation actions respectively.

Land degradation: Combatting land degradation was the dominant topic among mitigation and adaptation actions, in 206 and 350 times respectively, Table 1. Since land degradation is more of a problem than a sustainable land management practice, we examined management practices reported in Table 1 associated with it. Forest management (including afforestation and reducing deforestation) and agroforestry were the main SSM practices associated to combat land degradation.

Quantified actions: This screening resulted in 261 quantified mitigation actions and 110 quantified adaptation actions covering one or more land uses and using one or more indicators, Table 2. In the mitigation section of the NDCs, most of the quantified actions were reported by Africa (104), followed by LAC (84) and Asia and the Pacific (40) regions. 74 Parties reported a quantified action, mainly in forest land (158) and cropland (92). Most of the targets were expressed in hectares, percentages and tCO_2-eq. In the adaptation section of the NDCs, most of the indicators were reported by LAC (45), followed by the Asia and the Pacific (26) and Africa (22) regions. 43 Parties reported 110 quantified actions, mainly in forest land and cropland, data not shown. Most of the targets were expressed in hectares, percentage and number of trees.

Out of the 261 quantified mitigation actions, 39 of them were expressed in tCO_2-eq, of which 18 in the Latin America and Caribbean, 13 in Africa, 6 in Europe and Central Asia, and 1 in Asia and the Pacific and in NENA regions, Table 2. Although more than one land uses can be mentioned in an action, 76 percent of them estimated a climate change mitigation potential for forest land, and 29 percent of them for cropland. Out of the 110 quantified adaptation actions, 3 of them reported a target in tCO_2-eq (Chile and Pakistan), and 64 and 46 in hectares and percentage, respectively. Besides this, of the 281 adaptations actions associating a mitigation co-benefit, only 9 included a quantified target. Yet only 6 of these mitigation co-benefits were quantified in terms of tCO_2-eq, and 2 with a target expressed in ha. Quantified actions in tCO_2-eq were reported by Chile, but also Serbia and Nigeria. All mitigation co-benefits were associated to actions related to forest land.

As for the distribution of the SSM mentioned in mitigation and adaptation actions (Fig. 3), forest management, agroforestry, combatting land degradation and sustainable management were also the most

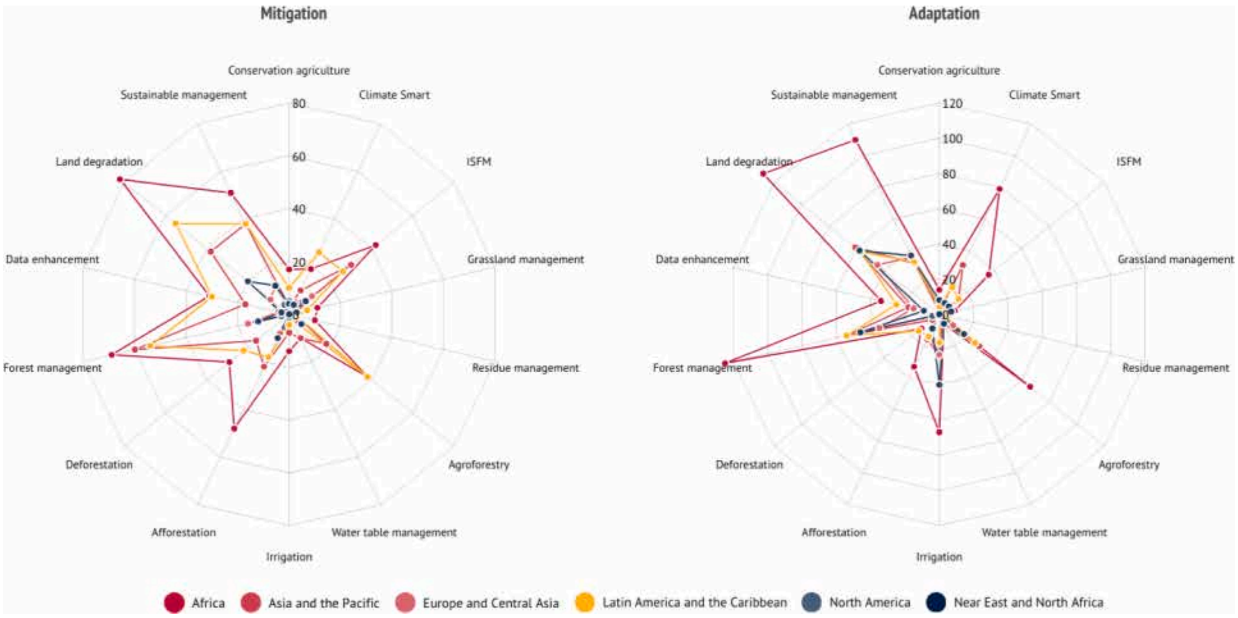

Fig. 2. Regional distribution of the sustainable soil management practices.

recurrent SSM within the quantified actions.

Actions explicitly mentioning SOC: In total 59 Parties explicitly mentioned SOC in their actions within the mitigation and or adaptation components of their NDCs, Table 3. SOC was mentioned in all regions except North America, Table 3 and Table 4 of the supplementary material. The LAC region accounted for about 50 % of the contributions, followed by Africa (33 %). The mitigation actions covered one or more land uses, with a predominance of cropland and forest land, 73 % and 41 % of the actions respectively, Table 4 of the supplementary material. The same pattern was observed for the adaptation actions, although actions did not always clearly relate to a specific land use, for example "Combating soil erosion and rehabilitating degraded lands". As a result, 38 % of the adaptation actions referred to cropland and 19 % to forest land, Table 4 of the supplementary material. The main land uses were forest land and cropland. Combatting land degradation, ISFM, agroforestry, conservation agriculture and sustainable management were the most mentioned SSM practices. Sixteen Parties reported actions with a quantified target, Table 3, but a few of them articulated targets expressed in tCO_2-eq within their actions, i.e. Albania, Guatemala and Uganda. Other common units reported in the targeted actions are non-GHG indicators: ha (18), % (11), farmers (6) and trees (3).

Albania reported SOC sequestration from adoption of SSM on cropland and grassland. Guatemala and Uganda reported on avoided deforestation with a quantified potential of carbon stock changes, although it is not clear if soil is the only one to be accounted in the climate change mitigation estimates. A number of countries explicitly indicated that SOC changes are included in their NGHGI, Table 3.

4. Discussion

This review aims at emphasizing the potential of SOC integration within climate change policies development using internationally recognized methodologies adopted by Parties to report to the UNFCCC, such as for their NGHGI. These same methodologies can be used to assess the climate change mitigation potential from policies across all sectors, including AFOLU and including the soil carbon pool.

A significant number of Parties (145) include soil in their mitigation and or adaptation actions, either explicitly or indirectly when mentioning SSM or when referring to a land use where the SOC stock is predominant, such as grassland or wetland. Among them, only 59 Parties explicitly mentioned SOC in their actions, of which 34 in the mitigation component and 43 in the adaptation component. This is 11 more Parties in mitigation and 27 more in adaptation as compared to Rose et al., 2020. The discrepancies between the number of Parties reporting on SOC and potential targets between this study and Rose et al., 2020 might come from new NDC submissions (Rose et al., 2020 looked at NDC submitted between September 2020–2022) but also from a different keywords list for the SOC category. However, as already mentioned by Wiese et al., 2021 and Wiese-Rozanova et al., 2021, the lack of inclusion of SOC or soil in the NDC does not mean that this thematic is not reflected in domestic policies and programs. Some of the reasons for not including SOC in their NDC are for example the need for Parties to prioritize food security and sustainable developments higher to climate change, and or the difficulty to accurately monitor changes in SOC or to collect the necessary activity data (i.e. hectares), limited resources, lack of technical capacity (Wiese et al., 2021; FAO & IGES, 2022). This and other reasons are largely discussed by the authors, and it is believed it should still be valid here. Nevertheless, the present analysis showed that few climate actions are quantified in terms of climate change mitigation potential, i.e. in tCO_2-eq, while some do have the necessary level of information to perform a preliminary carbon accounting at least using the basic tier 1 methodologies. This is the case of actions mentioning a target expressed in hectares or percentage, and eventually actions mentioning a sustainable soil management.

Soil-related IPCC methodology: The IPCC developed guidelines with methods for estimating and reporting GHG emissions and removals from all sectors of the economy, including the AFOLU sector. To estimate carbon stock changes and GHG emissions, Parties need activity data (in the AFOLU sector activity data mainly refer to areas) and information on the land use classification, land management, disturbances, climate and ecological zone, and soil type. Furthermore, IPCC provides a set of default Tier 1 emission factors (EFs), parameters, carbon stocks and carbon stock change factors to be used by countries in the absence of more accurate, country-specific data. It is important to note in cases where the 2006 IPCC Guidelines provide default methodologies and parameters, e.g. land uses, management practices, Parties are required to apply at least tier 1 methodologies as contained in these guidelines in order to develop their NGHGI estimates, including for the SOC pool (decision 18/CMA.1, UNFCCC, 2024c). Tier 1 estimates inherently are associated with high uncertainties (e.g. 90 % nominal error is assigned to the default reference SOC stocks for mineral soils by the 2006 IPCC Guidelines). Nevertheless, the same guidelines, as

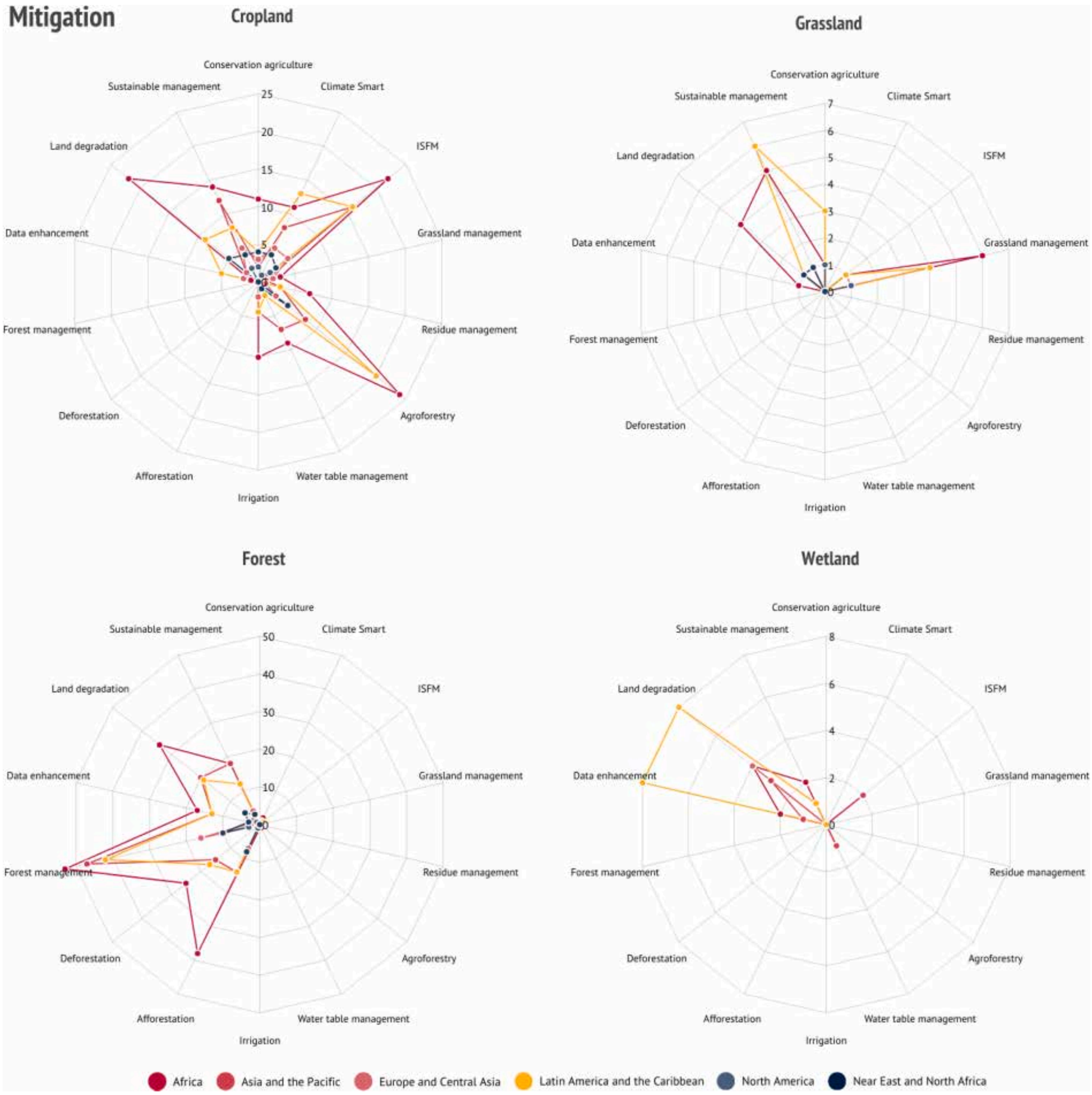

Fig. 3. Regional distribution of the sustainable soil management practices per land use types for the mitigation (top) and adaptation (bottom) components of the NDC database.

implemented by the relevant decisions (e.g. decision 18/CMA.1, UNFCCC, 2024c) recommend the application of higher tier methods with country-specific, more disaggregated and of higher resolution data, at least for key categories (i.e. categories that should be prioritised because their estimate have a significant influence on a country's total inventory estimates in terms of the absolute level, the trend or uncertainty in emissions and removals) in an effort to increase the accuracy of the estimates.

At tier 1 (IPCC default method), for a given area (in ha) changes in mineral SOC are estimated over a finite default period of time which is set to 20 years. The change of SOC is estimated using default reference SOC (per climate and soil type) values, and information related to the land use (forest land, cropland, grassland, wetlands, settlement and other land), management practices, inputs to soils and their changes over time, as described by equation 1, and provided in two formulations by the guidelines depending on the approach for land representation applied (see section 2.3.3.1 for further details, IPCC, 2006; IPCC, 2019).

$$\Delta C_{mineral} = (\boldsymbol{SOC}_0 - \boldsymbol{SOC}_{0-T})/\boldsymbol{D}$$

with

$$\boldsymbol{SOC}_{mineral\ at\ time(0)\&(0-T)} = \boldsymbol{\Sigma}_{c,s,i}(\boldsymbol{SOC}_{ref_{c,s,i}} \times \boldsymbol{F}_{LU_{c,s,i}} \times \boldsymbol{F}_{MG_{c,s,i}} \times \boldsymbol{F}_{I_{c,s,i}} \times \boldsymbol{A} \tag{1}$$

Where:

$SOC_{mineral\ at\ time\ (0)\ \&\ (0\text{-}T)}$ = Total mineral SOC stock at a defined time, in tC;

$SOC_{ref\ c,s,i}$ = SOC stock for mineral soils in the reference condition, in tC/ha;

D = Time dependence of mineral SOC stock change factors (the IPCC default time period for transition between equilibrium SOC values is 20 years), in yr.

c represents the climate zones, s the soil types, and i the set of management systems that are present

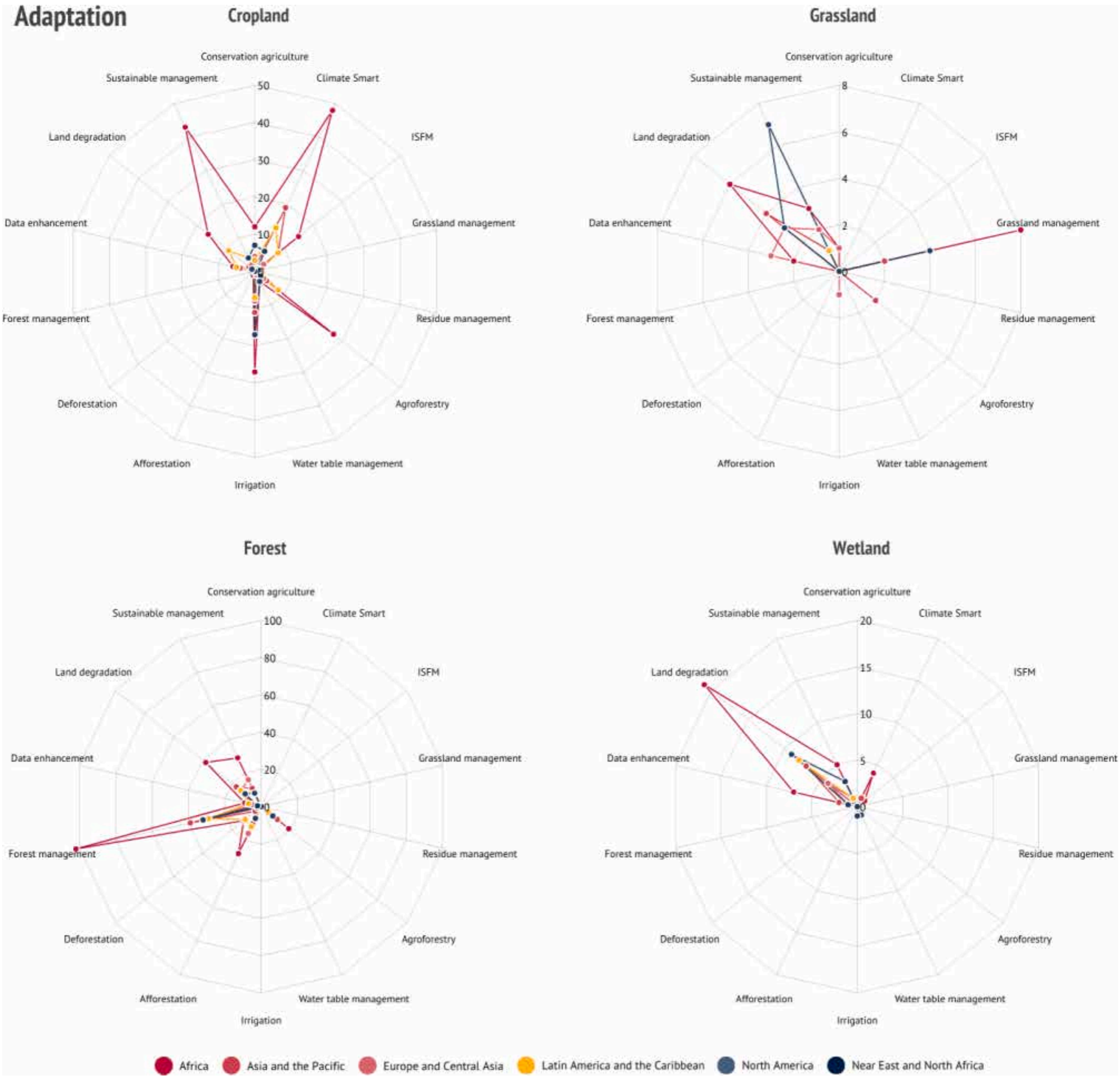

Fig. 3. (*continued*).

in a country.

F_{Lu} = Stock change factor for mineral SOC land-use system or sub-systems for a particular land-use, dimensionless;

F_{MG} = Stock change factor for mineral SOC for management regime, dimensionless;

F_{I} = Stock change factor for mineral SOC for the inputs of organic amendments; dimensionless and

A = Land area of the stratum being estimated, in ha.

Flu, Fmg and Fi are disaggregated by land-use category, temperature and moisture regime.

Therefore, SOC and the magnitude of SOC changes will depend on soil, climate, land-use category, and changes in soil management and input levels (for instance change from forest land to cropland or change from croplands with full tillage to cropland with reduced tillage). The equation also shows that the basic information needed to estimate SOC changes using the 2006 IPCC guidelines tier 1 method are: area, climate and type of soil, and the initial and final land use, land management and soil inputs. Following the IPCC guidelines, reference SOC stocks under native vegetation are disaggregated by mineral soil type and climate and provided in tonnes of carbone per hectare (tC/ha), see Table 2.3 of the IPCC, 2006 and IPCC, 2019, and Table 5.2 of the IPCC, 2013. Information on soil types and climate is thus required to retrieve SOCref at tier 1. In the absence of national datasets, soil type information can be derived from the USDA taxonomy or the Harmonized World Soil Database (HWSD, FAO & IIASA, 2023). To support Parties, the IPCC also provides a map for the IPCC climate zones (Fig. 3.A.5.1, volume 4, IPCC, 2006 and IPCC, 2019) and a decision tree to convert HWSD based soil into their respective IPCC categories (Figs. 3.A.5.3 and 3A.5.4, volume 4, IPCC, 2006 and IPCC, 2019). For the rest of the variables needed to estimate Tier 1 SOC stock changes (i.e. areas for the different land use classes, soil management practices and input levels, and their changes), national information from statistical sources or data from the field or using satellite imageries accessible from different platform such as ABC-Map (Dionisio et al., 2023) and Earthmap among others should then be collected. The IPCC guidelines provide default stock change factors which are associated with the different land uses (e.g., forest land,

Table 2
Regional distribution of the targets by target type from the mitigation (top table) and adaptation (bottom table) sections of the NDCs.

Region	ha	%	tCO_2-eq	tree	Farmers	USD
Africa	68	30	13	8	3	4
Asia and the Pacific	18	18	1	6	0	0
Europe and Central Asia	6	8	6	1	0	0
Latin America and the Caribbean	49	39	18	1	2	0
North America	0	1	0	1	1	0
Near East and North Africa	11	3	1	3	3	0
Total	**152**	**99**	**39**	**20**	**9**	**4**

Region	ha	%	tCO_2-eq	tree	Farmers	USD
Africa	16	5	0	1	1	1
Asia and the Pacific	12	14	1	4	0	2
Europe and Central Asia	4	2	0	2	0	0
Latin America and the Caribbean	28	20	2	1	1	0
North America	0	1	0	0	0	0
Near East and North Africa	4	4	0	3	0	1
Total	**64**	**46**	**3**	**11**	**2**	**4**

Note: one or more indicators could have been specified in the actions.

grassland), as well as with management practices (e.g., tillage for cropland, soil degradation or improvement state for grasslands) and with input levels (e.g., medium, high input), see table 5.5 and table 6.2 (IPCC, 2006; IPCC, 2019). These together with the SOCref values and the respective areas for the different strata (different combinations of land-use, management, input level per climate and soil type) provide all the necessary information that countries need to estimate ex-ante IPCC Tier 1 SOC changes from mineral soils.

Although Tier 1 estimates provide a first idea of SOC stocks and SOC stocks changes, large uncertainties in the SOCref and stock change factors must be acknowledged, as also briefly explained above. With regards to soil, this argument is also discussed by Sinitambirivoutin et al., 2024 (this issue). Nevertheless, with all uncertainties considered, we consider the IPCC Tier 1 methodology can still provide an entry point to estimate SOC stocks and SOC stock changes when no better national data sources are available.

Soil management practices with a SOC impact: The analysis made in this paper showed that there is a significant list of sustainable practices with a SOC sequestration co-benefit, Tables 1 and 3, and Fig. 3. Apart from some regional variations, combatting land degradation was one of the most recurrent topics, as also observed by Wiese et al., 2021 and Wiese-Rozanova, 2022. Land degradation is the result of human-induced actions, including land use and management practices which lead to the reduction or loss of the biological or economic productivity and complexity of rain fed cropland, irrigated cropland, or range, pasture, forest and woodlands (UNCCD, 2024b). Addressing land degradation implies avoiding further loss of SOC stock, preserving current carbon stocks and or enhancing them. We saw that forest management and agroforestry were the most frequent practices mentioned for that purpose. This is in line with a growing body of literature showing that agroforestry may enhance SOC stock, (FAO, 2017b; Feliciano et al., 2018; Cardinael et al., 2018; Chiartas et al., 2022; Mayer et al., 2022; Rolo et al., 2023). Some other management practices are described in Table 1. The commonly reported practices in cropland associated with the enhancement of SOC stocks were organic amendment, irrigation, tillage and leguminous. These practices are also reflected in the IPCC guidelines regarding soils, (e.g. Table 5.5, IPCC, 2006; IPCC, 2019). For example, shifting a cropland area from full tillage to reduced tillage can increase SOC stocks from 2 percent to 15 percent based on tier 1, depending on the climate, and without considering any soil inputs (IPCC, 2006). For grassland, rotational grazing allows reducing SOC stock losses or even contributes to increase SOC sequestration by reducing the time spent by livestock on pasture.

Table 3
Countries reporting SOC in their mitigation and adaptations actions, and targets if any.

Parties	Mitigation	Adaptation	Parties	Mitigation	Adaptation	Parties	Mitigation	Adaptation
Albania	2 [2, tCO_2-eq]		Haiti	1	1	Pakistan		2
Armenia	1		Iraq	1	1	Republic of Moldova *		1
Azerbaijan	1		Japan *	1		Rwanda *	4 [3, ha]	2
Bahamas	1	1	Jordan		2	Senegal	1	1
Benin		2	Kazakhstan		1	Seychelles		1
Bolivia * (Plurinational State of)	1 [1, ha] in cropland	2 [ha] one is the repetition of the mitigation action	Lao People's Democratic Republic		2	Sierra Leone	1	1
Brazil *	1 [1, %]		Lesotho		1	South Sudan	5	
Burkina Faso*		1	Liberia	4 [2, farmer]	1	Sri Lanka *		2 [1, %]
Cabo Verde	1[1, %]	1	Malawi	6 [2, ha]	2	Tajikistan		2
Chad	1	1	Mauritania	1 [1, ha]	1	Timor-Leste		
Chile *		1	Mauritius		1	Togo		2
China *	1	1	Micronesia (Federated States of)		1	Türkyie *	1	1
Congo		1	Morocco	1 [1, ha]		Turkmenistan	2	
Costa Rica	2	1	Mozambique	1	1	Uganda *	1 [1, tCO_2-eq]	
Democratic Republic of Congo		2	Namibia	1 [1, ha]		Uruguay *	4 [4, ha and %]	1 [1, %]
Djibouti	1		Nauru		1	Uzbekistan		1
Dominica *	4 [2, % & km^2]	1	Nepal	1 [1, %]		Vanuatu		1
Ecuador		1	Niger *		1	Viet Nam *	1	
El Salvador	12		North Macedonia	1		Venezuela (Bolivarian Republic of)		3
Guatemala	1 [1, tCO_2-eq]	3 [3, ha and %]	Oman		1			

Notes: Brackets report number of actions associated with a target and its type. * Parties that explicitly indicated in their NGHGI that SOC changes are included (based on GHG inventory information submitted to UNFCCC until 31.12.2023).

Shifting from a degraded grassland to a non-degraded grassland allows to increase SOC stock by 30 percent, according to tier 1 parameters (Table 6.2, IPCC, 2006; IPCC, 2019). Restoration of wetlands, through mangrove reforestation or restoration, contributes to the enhancement of SOC stock. The IPCC Wetlands supplement (IPCC, 2013) provides guidance for SOC sequestration from direct reseeding of mangroves, −1.62 tC/ha/yr. This is a global factor, i.e. unique for all mangroves whatever the type of climate or soil, (Table 4.12, IPCC, 2013), when using the tier 1 method. Williamson & Gattuso (2022), recently discussed the issues on the reliability of carbon accounting for coastal ecosystems (tidal marsh, mangroves and seagrass), without nevertheless acknowledging the numerous ecosystems services coastal blue carbon do provide. Last, avoiding loss of SOC stock also means reducing the pressure on the land, such as deforestation towards annual cropland, grazing, forest disturbance as fire, tillage, and/or shifting towards unsustainable management.

GHG-based targets: This analysis showed that only 33 % of the climate change mitigation measures and 8 % of the adaptation ones contained a target, GHG or non-GHG based. Of the 261 quantified mitigation measures and 110 quantified adaptation measures, only 39 climate change mitigation measures and 3 climate change adaptation measures provided a GHG target, i.e. in tCO_2-eq. This represents 15 % of the quantified mitigation contributions and 3.6 % of the adaptation contributions. But it also represents 5 % of the soil-related mitigation actions and 0.3 % of the soil-related adaptation actions. In addition, only 4 of the 261 mitigation actions, or 1.5 %, included a quantified SOC sequestration target (Albania, Guatemala and Uganda). The other quantified targets were generally expressed in hectares or as a percentage. Actions with targets expressed in hectares account for almost half of the quantified actions, for both mitigation and adaptation, 216 actions in total. Some of these actions have nonetheless minimal information to estimate soil carbon stock changes using the IPCC default method (Tier 1) when applying default stock change factors and parameters based at least on the most dominant climate and soil type at national level. For example, the climate change mitigation action from Mali "Reforest 76,000 ha per year" could be analysed based on some assumptions and accessible information: the initial land use could be determined from on field information or satellite imageries. The use of climate and global ecological zone (GEZ) maps of the IPCC, respectively Fig. 3A.2.1 and Fig. 4.1 (IPCC, 2006; IPCC, 2019), and the online map derived from the HWSD v2.0 (Sinitambirivoutin et al., 2024, this issue), could help to determine the type of climate, forest and soil type on these reforestation areas. The same applies to certain actions where the target is expressed as a percentage of a base year or any other reference for which it should be possible to find an area expressed in hectares. For example, for the action from Côte d'Ivoire "Reduce deforestation: reduce deforestation rates by 70 % by 2030 compared to 2015 levels ", it should be possible to track the number of hectares deforested in 2015, to estimate the number of hectares deforested by 2030, and therefore the SOC and biomass stock losses avoided from deforestation.

Soil carbon stocks and national inventories: In total 59 Parties (out of 167 NDC submissions) explicitly mentioned SOC in their mitigation and or adaptation components of their NDCs. However, only Albania, Guatemala and Uganda reported a GHG-based target. Based on the official communications to UNFCCC (NGHGI, National Communications, Biennial Update Reports (BUR)) all, except one, Annex I (developed) Parties have reported carbon stock changes from soils in the NGHGI in at least one land-use category, while a growing number of non-Annex I (developing) Parties included carbon stock changes from soils in their inventories.[2] Indeed, there is still a significant number of developing countries that face challenges, of different natures, in estimating and reporting emissions/removals from this carbon pool as described above (FAO & IGES, 2022). Uganda is among the Parties reporting SOC changes within their NGHGI. As presented in Table 3, other Parties that include SOC changes in their NGHGI are for example Bolivia, Brazil, Chile, Japan, Vietnam. Further to this, the analysis showed that some Parties are planning to add or enhance their soil data in their inventories. This is the case for some of the LAC Parties with their wetland ecosystems, Fig. 3. For this purpose, Belize, Chile, Costa Rica and Panama are planning one or more of the following actions: (i) to complete an assessment of the below-ground carbon stock of mangroves, (ii) to develop standardized metrics on wetlands and or use Chapter 4 of the wetlands supplement (IPCC, 2013), and or (iii) to manage, monitor and or conserve coastal wetlands. Other Parties that are planning to include wetlands in their inventories are Cabo Verde, Nepal and South Sudan. While it could be expected that soil would be part of the inventory on wetlands it is less clear for other ecosystems, in particular forests, as most of the SOC-based actions were associated with cropland before forests. A few Parties are planning to develop or improve their inventories on forest although this is not always clear if all carbon stocks including soil will be covered: Dominica, Guinea, Guinea-Bissau, Pakistan, Papua New Guinea, Solomon Islands, Timor-Leste and Tonga. The NGHGI from Parties to the UNFCCC contains the time series of emissions from sources and removals from sinks. Improving the completeness of the NGHGI, i.e. geographical, sectoral and categorical (sources/sinks) coverage is the prerequisite for planning appropriately mitigation actions, raising ambition in NDC from one cycle to the other one, in order to keep the temperature goal of the PA.

Accounting and reporting to the UNFCCC: Under the Paris Agreement, processes for tracking national efforts have been put in place to determine whether Parties are meeting their targets and whether the collective sum of individual contributions is on track to meet the temperature goal of the PA. The Enhanced Transparency Framework (ETF) has been established for reporting and review under the PA to ensure the transparency of mitigation and adaptation actions and of support, as per decisions 18/CMA.1 (UNFCCC, 2024c) and 5/CMA.3 (UNFCCC, 2024d). The purpose of the ETF is to provide a clear understanding of climate change action to support clarity and tracking of progress towards achieving Parties' NDC, including good practices, priorities, needs and gaps. The main report that Parties to the PA have to submit to the UNFCCC is the Biennial Transparency Report (BTR) which contains among other, the NGHGI, and information on tracking the progress made in the implementation and achievement of the NDC. Thus, to estimate the contribution of AFOLU policies and measures reported in the NDC, support the decision makers, enhance climate change contribution from one cycle to another (raise ambition), and track progress towards the NDC, Parties and other stakeholders will need appropriate standards or GHG accounting tools that align to the modalities, procedures and guidelines of the ETF.

To support Parties in this exercise, FAO developed a new GHG accounting tool, the Nationally Determined Contribution Expert Tool (NEXT) in 2022, (Schiettecatte et al., 2022a,b). The tool covers the AFOLU and Energy sectors. NEXT provides annual and cumulated estimate of the climate change mitigation potential of Parties' actions within their NDC, long term strategies and other communications to UNFCCC, as well as project, over a 30-years' time series. This time series allows users to estimate the climate change mitigation potential of past, ongoing and planned policies and measures. The tool relies on the provision of the PA's ETF, i.e. it uses the IPCC methodologies and default emission factors and carbon stock and global warming potential recommended to account, report and track on GHG accounting. Besides cumulated and annual estimates of the climate change mitigation potential of each action individually or combined, it provides a wide range of indicators to allow tracking the GHG according to their source. For example, NEXT provides estimates of the annual and cumulated GHG emissions and carbon removals from the soil compartment including

[2] The analysis considered the GHG inventory information submitted through the national communications to UNFCCC until 31.12.2023, assessing the Parties that explicitly indicated in their national GHG inventories that SOC changes are included.

N_2O emissions from managed soil, i.e. direct and indirect N_2O emissions from the mineralization of the soil organic matter. The tool also produces several SOC indicators following a request from the 4 per 1000 initiative. NEXT had already been used in the context of NDC analysis and enhancement, (Schiettecatte et al., 2022a), and can be used from a minimum of information to get a first estimate of climate change mitigation potential of a policy, measures, project or action. We discussed above the different actions that could benefit from this type of ex-ante analysis. For instance, the previous example from Mali "Reforest 76,000 ha per year" may result in a climate change mitigation potential (using the IPCC, 2006 and default stock change factors) of −30 million tCO_2-eq by 2030, shared between biomass gain about −15.5 million tCO_2 and enhanced SOC stock, −14.5 million tCO_2. This potential further increases to –138 million tCO_2 by 2050, with a third of it within soil. The following assumptions were used to run a GHG analysis: (i) the reforestation activities span from 2020 to 2030 and will be implemented in the southern part of the country, (ii) the dominant land use in this area is an annual cropland (determined from the land cover ESA Land Cover CCI v2.1.1, ESA, 2024), (iii) the dominant IPCC soil class at national level is a low activity clay soil, and (iv) the dominant climate is tropical dry. Another example is one based on a target expressed in %, in Côte d'Ivoire "Reduce deforestation: reduce deforestation rates by 70 % by 2030 compared to 2015 levels". In that case, a quick analysis to estimate the mitigation potential from reducing the deforestation could start with the following assumptions: (i) the deforestation rate in 2015 was 112,886 ha based on the second BUR, (UNFCCC, 2024e), (ii) The BUR mentions that the "deforestation is driven by agriculture (62 %), logging (18 %), infrastructure expansion (10 %), mining (8 %), bush fires (2 %)". In an ex-ante approach, we can simplify the analysis and assume 60 % of the deforestation is towards cultivated land, and 40 % towards other land, (iii) the deforestation will mainly concern the tropical moist forest area, and (iv) the dominant IPCC soil class at national level is a low activity clay soil. Over the commitment period (2020–2030), 1,241,746 ha should have been deforested (745,048 ha towards agricultural land, and 496,698 ha towards other land) if the action was not implemented (i.e. baseline scenario), but its implementation reduced the deforestation to 372,524 ha (223,514 ha towards agricultural land and 149,910 ha towards other land). Reducing the deforestation rates by 70 % by 2030 compared to 2015 levels allows avoiding emissions and preserve carbon stock of about −500 million tCO_2-eq, of which about −485 million from the biomass, −14 million from the SOC stock changes, and about −1.3 million tCO_2-eq of N_2O coming from the mineralization of the soil organic matter as a result of the land use change. As we can see NEXT is providing results that combine different carbon and nitrogen dynamics, while providing basic information, i.e. implementation period, hectares, climate and soil type. For both Mali and Côte d'Ivoire, we used the dominant soil type provided in the "home" worksheet of NEXT. The distribution of the soil is also accessible from the "help" worksheet of the tool through a link to an online map. The same type of maps for the distribution of the climate, the global ecological zone and the histosols are also available from the "Help" worksheet. The NEXT analyses are available in the supplementary material.

5. Conclusion

By 2025, Parties will have to submit to UNFCCC a new or updated NDC. As part of the PA cycle, each submission shall have more ambitious climate commitments as compared to the previous one. It is thus expected that Parties will raise their ambition regarding their actions on GHG emissions reductions and carbon removal. Despite soil is central in food security, ecosystems services provisioning, and the global carbon cycle, this study showed that the climate change mitigation potential from soil-related actions, i.e. in tCO_2-eq, is still underrepresented in the NDCs. However, many soil-related actions are already sufficiently well formulated on soil management practices and objectives to carry out an IPCC tier 1 ex-ante GHG accounting. Several Parties are also planning to enhance their data related to soil to also improve their GHG inventories. We showed that preliminary analysis can be done from few variables: period of implementation, areas expressed in hectares, soil type and climate. Some of these information can be easily collected or complemented from different databases (FAOSTAT, Forest Resources Assessment, maps, among others) and or national document (a forest reference level, national statistics, national policies, BUR for example). Dialogue between policy makers, agricultural experts, and technical experts in charge of the NGHGI can also help to refine the analyses and thus reduce the uncertainty; for example, by sharing information, such as among others: land management (tillage) and inputs of a specific crops, the type of agroforestry systems, the quantity of fertilizers used and eventually some national carbon stock when available. Ex-ante GHG estimates using tools, such as NEXT, could be used by policy makers to prioritize policy implementation areas and/or obtain higher tier information (soil carbon stock, biomass growth rate) or a higher level of disaggregation (disaggregated implementation area on climate and soil type, land use type and its associated management and inputs for cultivated land, hectares, mortality rate) to improve the carbon balance (or GHG accounting). These estimates are thus an entry point for collaboration between the experts involved the NDC formulation, the NGHGI development and the national planning, as well as universities and experts from the Rio Conventions. Enhancing data management systems and technical capacities to undertake ex-ante mitigation analyses is key to ensuring that national planning processes and target setting are credible, feasible and on track to achieving the long-term temperature goals of the PA.

CRediT authorship contribution statement

Laure-Sophie Schiettecatte: Writing – original draft, Methodology, Investigation, Conceptualization. **Iordanis Tzamtzis:** Writing – review & editing, Writing – original draft. **Jean-Luc Chotte:** Writing – review & editing. **Krystal Crumpler:** Writing – original draft, Resources. **Clara Proenca:** Visualization. **Mirella Salvatore:** Writing – review & editing. **Maidie Sinitambirivoutin:** Writing – original draft. **Liesl Wiese:** Writing – review & editing. **Martial Bernoux:** Supervision.

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.

Acknowledgement

This work was funded by the German Federal Ministry of Economic Cooperation and Development and the German Federal Ministry for food and Agriculture, the Scaling up Climate Ambition on Land Use and Agriculture through NDCs and NAPs program (SCALA), the French Ministère de l'agriculture et de la souveraineté alimentaire.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2025.108805.

Data availability

Data will be made available on request.

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