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Factoring out Natural and Indirect Human Effects on Terrestrial Carbon Sources and Sinks

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Abstract

The capacity to partition natural, indirect, and direct human-induced effects on terrestrial carbon (C) sources and sinks is necessary to be able to predict future dynamics terrestrial C sinks and thus its influence on atmospheric CO_2 growth. However, it will take a number of years before we can better attribute quantitative estimates of the contribution of various C processes to the net C balance. In a policy context, factoring out natural and indirect human-induced effects on C sources and sinks from the direct human-induced influences, is seen as a requirement of a C accounting approach that establishes a clear and unambiguous connection between human activities and the assignment of C credits and debits. We present options for factoring out various groups of influences including climate variability, CO_2 and N fertilization, and legacies from forest management. These are: i) selecting longer accounting or measurement periods to reduce the effects of interannual variability; ii) correction of national inventories for inter-annual variability; iii) use of activity-based accounting and C response curves; iv) use of baseline scenarios or benchmarks at the national level; and v) stratification of the landscape into units with distinct average C stocks. Other, more sophisticated modeling approaches (e.g., demographic models in combination with forest inventories; process-based models) are possible options for future C accounting systems but their complexity and data requirements make their present adoption more difficult in an inclusive international C accounting system.

Keywords: AFOLU, carbon cycle, forests, Kyoto Protocol, LULUCF, Marrakesh Accords, C sink processes, C source processes, factoring out.

1. Introduction

There is considerable interest in assessing our understanding and capacity to partition natural, indirect and direct human-induced effects on terrestrial carbon (C) sinks and sources. The attribution of C flux quantities to their underlying drivers is a prerequisite to understanding the influence of the terrestrial biosphere on future atmospheric CO_2 growth, and the C fluxes that may be amenable to intervention by human management (Canadell et al., 2000, 2007; Global Carbon Project, 2003). Failure to understand the processes that govern the current increase of atmospheric greenhouse gases (GHGs) may lead to incorrect projections of their future accumulation rates and associated impacts on climate change.

New international policy developments emerged from the Marrakesh Accords, which were adopted by the COP11/MOP1 of the United Nations Framework Convention on Climate Change (UNFCCC) in Montreal in November 2005. These suggest the need for improved scientific understanding in support of the development of effective climate change mitigation policies as well as for adequate reporting of progress achieved in reducing GHGs emissions by the Parties to the Kyoto Protocol. In this context, factoring out, i.e., the partitioning of the contributions of direct human influences on C sinks and sources from natural and indirect influences, is receiving new attention.

Marrakesh Accords decision 11/CP.7 on Land Use, Land-Use Change and Forestry (LULUCF) invited the Intergovernmental Panel on Climate Change (IPCC) to "develop practicable methodologies to factor out direct human-induced changes in C stocks and greenhouse gas emissions by sources and removals by sinks from changes in C stocks and greenhouse gas emissions by sources and removals by sinks due to indirect human-induced and natural effects (such as those from carbon dioxide (CO_2) fertilization and nitrogen (N) deposition), and effects due to past practices in forests (pre-reference year), to be submitted to the Conference of the Parties at its tenth session" (FCCC/CP/2001/13/Add.1, English, Page 55).

The issue was included to ensure the development of appropriate and fair accounting rules for future use of the Kyoto Protocol (i.e., after the First Commitment Period) that would exclude credits that resulted from indirect effects of human action or global change. Although the primary focus of the negotiation was on avoiding undue credits, the Marrakesh Accords specified that factoring out methodology should address both sources and sinks, thus undue debits are also subject to factoring out.

The Marrakesh Accords were mostly concerned with the indirect human-induced effects of increased atmospheric CO_2 and N deposition, and the effects of past land-use practices (pre-reference year 1990). These factors are, however, part of a broader set of natural and anthropogenic processes (with positive and negative effects) that contribute to the current net terrestrial C exchange. The negative effects (emissions) have so far received much less attention in the negotiations. These broader set of factors includes, among others, the effects of pollution including tropospheric ozone, agricultural effects on soil erosion and sedimentation, wildfire emissions, and the positive and negative feedbacks coming from natural and anthropogenically driven climate variability and change.

Two IPCC expert groups analyzed the issue (IPCC, 2002, 2003) and concluded that the current state of science is presently insufficient to develop practicable and sound scientifically-based methodologies to appropriately separate direct and indirect human-induced effects from natural effects on terrestrial C sinks and sources within the timeframe requested in the Marrakesh Accords. Some level of attribution could be achieved for some direct human influences. A third expert group was convened by the US National Academy of Sciences (NAS, 2004) and came to similar conclusions.

We acknowledge that the factoring out issue refers to more than the issue of excluding natural and indirect effects on *C stock changes and non-CO_2 GHG emissions* as part of LULUCF activities like afforestation, reforestation, deforestation, forest management, cropland management, grazing land management and revegetation. Under the Kyoto Protocol there is also a need to determine whether these activities themselves are direct human induced. For example, deforestation may or may not be direct human induced: a wildfire resulting from a drought event (natural condition) that leads to the permanent loss of forest cover may only be termed direct human induced deforestation if the reason for lack of regrowth is a non-forest land use. The emergence of new forest may only be termed *direct human induced afforestation or reforestation* if human land-use decisions are involved. The discussion of when an activity is direct human induced is beyond the scope of this paper.

In this paper, we first provide a brief synthesis of the current knowledge of the processes driving terrestrial C sinks and sources at the global scale, and the potential for attributing C fluxes to processes with current observations and modeling capabilities. This understanding is essential for designing C accounting methodologies in support of the development of an international C management regime (specifically a post 2012 LULUCF institutional framework) that could take account of the influence of natural and indirect effects in the future source/sink crediting system (section 2). Secondly, we discuss critical considerations in order to develop factoring out methodologies that would address the request in the Marrakesh Accords and could inform post 2012 climate policy development (section 3). Thirdly, we present a number of possible methodologies that address components of the factoring out issue and contribute to practical methodologies that could be used in a policy context (section 4). Although the focus of the paper is on C processes, stocks and fluxes, the relevance of addressing the factoring out issue in sections 3 and 4 equally applies to the full set of greenhouse gases considered in the Marrakesh Accords.

2. Key processes affecting global terrestrial carbon sources and sinks

Since early attempts to explain the processes responsible for the biospheric C sink (Friedlingstein et al., 1995), a complex picture has emerged which invokes multiple processes with strong spatial and temporal dynamics. They can be grouped into: i) processes driven by atmospheric and climate variability and change; and ii) processes driven by land-use change and management (Table 1).

2.1 Processes driven by atmospheric and climate variability and change

CO_2 fertilization. There is little doubt that increasing atmospheric CO_2 can increase C uptake, and possibly C sinks, but the magnitude and the spatial distribution of these impacts are still debated (Morgan et al., 2004; Körner et al., 2006). Based on fundamental physiology and climate interactions we know that the CO_2 fertilization effect is not uniform through the world's ecosystems and that it is likely to result in the largest sink enhancement in the tropics. Ciais et al. (2005a) using a combination of biogeochemical modeling, atmospheric measurements and forest inventories showed that CO_2 fertilization could explain as much as 100% of the biospheric tropical sink which, with large uncertainties, is estimated to be of similar magnitude but of opposite sign as emissions from deforestation, 1-2 GtC yr^{-1} (Sabine et al., 2004). CO_2 fertilization could also explain 50% of the Siberian sink, but only as much as 10% of the European sink. In Europe, other processes are likely to play a larger role such as: i) management practices, including the regrowth of forests after heavy logging and abandonment of agricultural land during the 20^{th} century, ii) N deposition, and iii) changes in climate variability and disturbances.

Most types of ecosystems show increased plant growth (Net Primary Productivity, NPP) by 10% to 25% at double current atmospheric CO_2 concentrations (Mooney et al., 1999; Nowak et al., 2004; Luo et al., 2005; Norby et al., 2005). At the current rates of increase in atmospheric CO_2 concentration, this would correspond to an increase in NPP of a few tenths of a percent per year, which cannot be detected with current methodologies. Responsiveness declines over time.

NPP is also intimately linked to the interacting cycles of carbon, water and nutrients. Plant responses to increasing CO_2 can be curtailed through insufficient availability of nutrients. The combined effects of these processes are illustrated here through simulations with the forest growth model CenW at four different locations with contrasting climates (Figure 1; Kirschbaum, 2004).

Individual responses to doubling CO_2 can range from close to zero under nutrient-limited (especially N) and well-watered conditions (Oren et al., 2001, Reich et al., 2006) to increases of up to 70% under well fertilized and water-limited conditions (Morgan et al., 2004). Direct CO_2 physiological responses, which express themselves best when neither water nor nutrition are limiting, are intermediate in their magnitude and differ with predominant temperature (Fig. 1). This shows that there is no unique sensitivity of plant productivity to increasing CO_2 concentration or temperature. Different combinations of changes in CO_2 and other aspects of global change therefore imply different overall effects on plant productivity for different systems in different geographical regions.

In addition to interactions with nutrient and water availability (Morgan et al., 2004), species or even clones within species (Kaakinen et al., 2004) and stand age also play a role, with younger trees/stands being more responsive than mature forests (Körner et al., 2006). In principle, it would be possible with the aid of a biogeochemical model and multi-factorial experiments to attribute the individual and interactive effects of these various drivers.

Nitrogen deposition. Improved N nutrition after deposition of atmospheric N, on its own and interactively with the CO_2 fertilization effect, is an important C sink process in N-limited regions. This N originates from the combustion of fossil fuels, biomass burning or from the volatilization of N from organic or inorganic sources in agriculture N fertilization. Nitrogen fertilization is probably most important in Europe and the Eastern US because of the large quantities of N deposition and because many forests are N limited. Forests are the ecosystems that can take most advantage of additional N due to the high C:N ratio of wood. Globally, N deposition may have accounted for about 0.19-0.25 GtC yr^{-1} of the 0.2 to 1.4 GtC yr^{-1} net C sink during the 1980s and 90s (Nadelhoffer et al., 1999; Sabine et al., 2004; Galina Churkina, in preparation). In the future, further enhancement of the terrestrial sink will probably be more due to CO_2 fertilization than N fertilization because the expected larger future growth of the CO_2 forcing and the negative effects on additional N depositions in regions already N saturated (Canadell et al., 2007). Increased N deposition in the tropics (Hall and Matson, 1999) and in regions dominated by cropland (e.g., China) are likely to show on-going but limited effect on C sinks.

Air pollution. Associated with the increase in atmospheric N deposition and GHGs emissions in most industrialized countries, harmful levels of different air pollutants are released. The emission of primary pollutants that are harmful to vegetation and human health, such as SO_2 and HF, are being reduced or are restricted to localized areas, whereas secondary pollutants like tropospheric ozone are still a problem in large regions of the world like Europe and North America, and they are becoming an increasing problem in Asia (Sanz and Millán, 1999; Ashmore, 2005). Chronically-enhanced levels of tropospheric ozone are likely to be curtailing the C sink strength of forest trees and ecosystems (Karnosky et al., 2001; Körner, 2003; Kozovits et al., 2005). Tropospheric ozone pollution has even shifted from a regional to a global issue due to intercontinental transport of O_3 (Derwent et al., 2004). Background and/or peak ozone levels are predicted to stay high or even increase (Fowler et al., 1999).

Plant production and climate change/variability. It is estimated that global terrestrial NPP has increased by about 6% (3.4 GtC) over the last two decades largely as the result of extending the growing season in high-latitude ecosystems because of global warming (Nemani et al., 2003). This increase in NPP may lead to an increase in C sequestration although the concomitant increase in soil respiration may cancel out the C gains in some regions. New observations on the dampening of the C sink strength due to increased climate variability are challenging the hypothesis that C sink will be enhanced with further climate change. An analysis of the entire Northern Hemisphere shows that since 1994 the acceleration of C uptake during early spring was cancelled out by decreased uptake during summer, probably due to hotter and drier summers in mid and high latitudes (Angert et al., 2005). The 2003 heat wave in Europe alone reduced gross primary productivity by 30% which resulted in the region becoming a CO_2 net source to the atmosphere by 0.5 GtC yr^{-1} (Ciais et al., 2005b). That is the equivalent of about 4 years of C accumulation in these systems. Increased temperatures and climate variability can also lead to shifts in the behavior of pests in large areas leading to losses of C (i.g., *Lymantria sp.* attacks to perennial oaks, mountain pine beetle) (Caroll et al., 2004)

Soil Respiration and climate change/variability. In the absence of water limitation, higher temperature results in faster decomposition of soil organic matter (SOM), dead wood and litter C pools, and thus higher heterotrophic respiration (Kirschbaum, 2000; Rustad et al., 2000; Davidson and Janssens, 2006). General Circulation Models (GCMs) fully coupled with C cycle models show that increased soil respiration in a warmer world can yield an additional 50 to 200 ppm in the atmosphere by the end of this century (Cox et al., 2000; Friedlingstein et al., 2006) although the magnitude of these changes may be exaggerated by the simple structure of soil-carbon models used in these global simulations (e.g., Jones et al. 2005). Increased intensity of droughts due to higher temperatures can lead in some regions to a decline of soil respiration with a simultaneous decline of gross primary productivity (Angert et al., 2005; see also section on climate change and variability above).

Carbon stocks in two particular soil types can have substantial influence on the atmospheric CO_2 growth. The first is peatland soils which contain over 400 GtC world-wide (Gruber et al., 2004). In some regions these are subject to climate change, drainage and land-use changes, which expose the SOM to aerobic conditions suitable for increased decomposition. The second soil type is permafrost soils which contain over 900 Gt of frozen C and are already thawing due to the rapid warming in high latitudes (Zimov et al., 2006). Preliminary analyses suggest that by the end of this century as much as 200 ppm CO_2 could be added to the atmosphere from these vulnerable C pools (Gruber et al., 2004).

Natural disturbances. Changing climate and land use alters the frequency and intensity of disturbance regimes and their net contribution to atmospheric CO_2 growth. The global annual C flux to the atmosphere from savanna and forest fires (excluding biomass burning for fuel and land clearing) is estimated to be in the range of 1.7 to 4.1 GtC yr^{-1} (Mack et al., 1996). Other disturbances, such as insect attacks, can also have major impacts on both forest C dynamics and forest age-class structure (Kurz and Apps, 1999). A recent increase in Mountain Pine Beetle impact in British Columbia (Canada) is attributed, in part, to the relatively mild winters which contributed to high survival of overwintering beetle populations (Caroll et al., 2004).

In the long-term or over large spatial regions, C losses from disturbances may be compensated by the C gains during vegetation regrowth. Regional-scale sinks or sources are often the result of changes in the frequency, type or intensity of disturbances (Kurz et al., 1998; Kurz and Conard, 2005). A C imbalance is created during the transition from one disturbance regime to another: a C sink occurs when the frequency of disturbances is reduced, and a C source when the frequency of disturbances is increased. For instance, fire exclusion during the twentieth century in many countries has resulted in an increase of biomass in forests and woodlands (Luger and Moll, 1993; Houghton et al., 2000; Mouillot and Field, 2005), and the potential exists for further biomass accumulation. Increases in the area burnt over the last two decades in boreal forests in the USA, Canada and some parts of Europe are changing a long-term trend of C accumulation into one of predominant C release (Kurz and Apps, 1999; Mouillot and Field, 2005). Formation of highly recalcitrant charcoal due to fire may possibly make a significant contribution to long term C sequestration, but remains an elusive quantity to confidently quantify (Forbes et al., 2006).

2.2 Processes driven by land-use change and management

Vegetation regrowth, thickening and encroachment. Forest and shrubland regrowth, thickening, and encroachment are processes responsible for substantial human-induced C sinks. Forest regrowth on abandoned agricultural land has been identified as one of the most significant process to explain the net C sink in the Northern Hemisphere (USA: Houghton et al., 2000 and Pacala et al., 2001; Europe: Janssens et al., 2005). This abandonment has resulted in a significant expansion of relatively young forests with high growth rates.

Woody thickening and encroachment in semi-arid regions and savannas, largely due to fire suppression policies and pasture management, accounts for 22-40% of the US sink (0.12-0.13 GtC yr^{-1}; Pacala et al., 2001) and probably creates a significant component of the C sink in Australia (Gifford and Howden, 2001; Burrows et al., 2002). This process is among the least constrained quantities of regional C budgets.

Afforestation and reforestation. The establishment of new forest plantations as a direct human induced activity has not yet had much effect on the global strength of the terrestrial C sink. There are, however, regional sinks which have been greatly enhanced by afforestation programs such as in China where newly planted forests have sequestered 0.45 GtC since the mid-1970s (Fang et al., 2001). Large potential exists for future enhancement of the C sink by afforestation and reforestation. Greater adoption of biofuels or use of wood products may provide additional incentives for the establishment of new plantations.

Deforestation. Historically, conversion from natural vegetation to croplands has reduced global NPP by about 5% and released 182-199 GtC to the atmosphere (DeFries et al. 1999). Overall, changes in land use and cover since 1850 are responsible for 33% of the increased concentrations of CO_2 observed in the atmosphere (Houghton, 1998), 68% of which are due to cropland establishment (Houghton, 1999). There are a number of estimates of emissions from deforestation for the decades of the 1980s and 90s which range from 0.8 to 2.2 GtC yr^{-1} (DeFries et al., 2002; Houghton, 2003; Archard et al., 2004).

Agricultural practices. Improved agricultural practices in C depleted soils can create modest C sinks. For instance, the introduction of conservation tillage in the USA has increased soil organic matter (SOC) stocks by about 1.4 Gt over the past 30 years (Donigian et al., 1994), with the potential to store a further 5 GtC over the next 50 years (Kern and Johnson, 1993; Lal et al., 1998). Similar effects with magnitudes of about 10 MtC yr^{-1} have been estimated in Canada (Boehm et al. 2004). Globally, agriculture has been (and still is) a large source of C and non-CO_2 greenhouse gases, in particular CH_4 and N_2O, which for some land uses are of greater importance in greenhouse terms than CO_2 emissions and removals.

Erosion and burial. Cropping is estimated to lead to 10-100 times the natural-background levels of soil erosion, stimulating the increase of sediment load into the world's rivers by 2.3 Gt yr^{-1} compared to rates in pre-agricultural times (Syvitski et al., 2005). Of the total C in rivers, about 0.4 GtC yr^{-1} is total organic carbon and 0.4 GtC yr^{-1} is dissolved inorganic carbon (Richey, 2004). Part of this C is intercepted by dams and wetlands and the rest reaches the coastal zones where it is largely oxidized and returned to the atmosphere. Riverine transport can be a significant flux source of C in regions such as West Siberia and Borneo where peatlands are abundant. Globally, estimates of the net C sinks due to sediment burial is as high as 1 GtC yr^{-1} (Smith et al., 2001), but this estimate remains highly unconstrained and in need of further investigation.

2.3 Factoring out at the global and regional scales

At global and regional/national scales, large uncertainties reamin about the relative importance of the multiple interacting processes driving terrestrial C sources and sinks. These uncertainties are demonstrated by the current debate on the relative importance of the processes driving the net C sink in the Northern Hemisphere which is estimated to be 1-3 GtC yr^{-1} (IPCC 2001). Many terrestrial biogeochemical models drive the current and future net C exchange by simulating photosynthesis (C uptake) and heterotrophic respiration (C emissions). Despite the large role these two process play, most models still only account for a small number of source and sink processes, in particularly missing those relating to land use and management. Land cover changes such as deforestation enter into the models only as an external driver. Recent evidence suggests that forest regrowth and woody thickening due to the abandonment of cropland, fire suppression policies, and changes in the periodicity of insect outbreaks, may actually be the dominant processes to explain the current net C sink in some regions (Caspersen et al., 2000; Hurtt et al., 2002). In Canada, dominant factors in determining the net C balance are natural forest and insect disturbances regimes (Kurz and Apps, 1999).

Wrongly attributing processes responsible for the current C sink could be seriously misleading. For instance, if the sink is largely the result of recovery following land-use change or sudden shifts in management (e.g., cropland abandonment), but the sink is wrongly attributed to CO_2 fertilization and climate change (as it is currently attributed in carbon-climate models), then we are probably overestimating the potential future C sink of the terrestrial biosphere, and future climate change will proceed faster than currently predicted. This is because the sinks from vegetation regrowth and thickening will decrease as forests mature within the next few decades, while CO_2 fertilization could increase as atmospheric CO_2 increases up to a physiological saturation point likely to be reached later in this century (Canadell et al., 2007).

If the ultimate aim were to factor out the effect of each single process on C sources and sinks, one would also need to consider the interactions between processes driven by climate and atmospheric change, and between the processes driven by land-use change and land management. That makes the separation of individual factors even more difficult, if not impossible. For example, the CO_2 fertilization effect is greatly enhanced by N deposition, and in some instances, there may be no growth enhancement by elevated CO_2 effect unless additional N is available (Fig. 1). Likewise, CO_2 and N fertilization interact with forest regrowth, with larger effects observed in young stands, and smaller or no effects in mature forests (Körner et al., 2006). A second example is the interaction between more frequent dry-hot summers and biomass accumulation in forest due to fire suppression policies in boreal and temperate forests. The result has been a rapid shift of fire regimes in Boreal North America and parts of Europe (Mouillot and Field, 2005) for which the individual drivers (e.g., excessive biomass accumulation, drier summers) cannot be separated out because of the way they interact.

In summary, there has been significant progress over the last decade in understanding and quantifying the key processes affecting terrestrial C sinks and sources. We now have a good understanding of the multiple processes involved and we can describe their relative importance with growing certainty but still with some difficulties on their interactions with each other. Biogeochemical modeling is incorporating this new information and finding appropriate data to initialize and constrain models. Although this evolution is taking place very rapidly, it will be many years before we have a global C budget with good attribution of sources and sinks for the major C processes, reasonable spatial resolution and uncertainty estimates that are within acceptable limits.

3. Factoring out in the context of international GHG policies

Although factoring out was a significant issue in the negotiations it was not considered practicable to explicitly factor out a direct human component for the First Commitment Period (2008-2012) of the Kyoto Protocol. Instead, this aim was achieved indirectly through definition of specially defined land-use change activities (i.e., Article 3.3 of the Kyoto Protocol) and specific accounting rules for land use activities including country specific caps on allowable credits and debits for forest management and net-net accounting for cropland management, grazing land management and revegetation under Article 3.4. However the discussions on factoring out natural and indirect human-induced effects on C sources and sinks from those of direct human-induced activities re-emerged during the negotiations of 11th Conference of Parties to the UNFCCC and First Meeting of Parties to the Kyoto Protocol (Montreal, November 2005) as a potential issue for post 2012 LULUCF accounting rules.

The overall aim of GHG accounting rules was to provide incentives for individual countries or land holders to carry out actions that reduce C emissions and enhance sinks, in order to reduce net emissions to the atmosphere. That led to the intense discussions under the initial Kyoto Protocol negotiations for the First Commitment Period to develop appropriate rules. The aim was to translate the stated intention of encouraging land-use choices into rules to help mitigate emissions and enhance removals without introducing unintended consequences. Carbon sequestration resulting from the so called "indirect effects of climate change" and "past practices" (from activities before 1990) was considered a windfall sink to the Kyoto Protocol parties with commitments.

Thus, practical ways to separate out the direct human component from other effects in C accounting will strengthen the connection between new human activities and resultant C credits and debits. We know that natural or indirect human effects could significantly add to or negate the direct human effects leading to undue credits or debits and a decoupling of the incentives for further management changes to reduce net emissions. This would be perceived by stakeholders and the policy-making community in different ways.

On one hand, if natural or indirect effects increase sinks in some countries, then there is less need to curtail the emission of fossil fuels to achieve agreed emission targets. This would be seen as unfair by other countries that can only achieve similar targets through hard choices in their use of fossil fuels.

On the other hand, if natural or indirect effects increase sources, then countries will be reluctant to include human management of the terrestrial biosphere in the accounting systems as it would make it even harder for affected countries to meet their agreed commitments. For example the risk that events such as the European drought of 2003 or extreme fire years can cancel out any gains from human activities over multiple years may simply be perceived as too large. Exclusion of land-use options would, however, forgo one valuable option for cost-effective management of net emissions to the atmosphere.

Biospheric C stocks are continuously changing in response to both natural and human-induced processes. While the sum of all changes in C stocks can be empirically observed, and methods are continuously improving to make better observations, these observations alone cannot tells us what part of these C stock changes should be debited or credited to specific countries, land owners or activities.

Section 2 makes it clear that there are still significant gaps in our basic scientific knowledge that prevent us from being able to factor out the interacting natural- and human-induced influences on terrestrial C exchanges. However, in a policy framework we do not need to factor out all influences. Instead it is only necessary to distinguish between impacts of direct human-induced activities from the combined impacts of all other natural and indirect human-induced factors (Table 2). This separation will allow quantification of the sinks and sources resulting from direct human activities, and therefore the quantities that can be credited or debited in accounting systems.

Spatial scale is important in assessing what can be factored out. Scales relevant to policy are often smaller (e.g., project level and are limited to managed land categories) than those of an Earth System context, and they may have fewer processes affecting the net C balance. There are certain global effects that always operate everywhere such as CO_2 fertilization or climate variability and change, but others like dominant land use influences are specific to regions or projects.

3.1. Addressing the needs of the Marrakesh Accords and accounting beyond 2012

From a Marrakesh perspective, many of the issues above can be partially resolved because the request for information is limited to distinguishing the direct human-induced influences on C sources and sinks (from those induced indirectly by human activities, natural processes, and past practices in forests). The goal is to factor out the combined natural and indirect-induced contribution to C sources and sinks from the joint contribution of all direct human-induced effects. There is neither a requirement to separate the influence of each single factor contributing to direct and indirect human-induced effects nor a requirement to separate natural effects such as climate variability from long-term climatic trends.

We could address the Marrakesh request strictly from the perspective of the definition of human activities in the framework of the Kyoto Protocol which encompasses afforestation, reforestation, and deforestation since 1990 and elected activities under Article 3.4., and ignore all other lands and practices as for the First Commitment Period. In this case factoring out may not necessarily require large advances in scientific understanding but, for instance, a comprehensive monitoring of land areas could help significantly. With such monitoring, it would be possible to decide for each land unit whether a direct human change in land-use or management activity has taken place.

Locally or regionally, the most important events are land-use changes as they can result in large changes in C stocks. Deforestation (followed by changing land use to non-forest vegetation) can lead to a large and rapid loss of C stocks that is directly human induced. Afforestation or reforestation can lead to large increases in C stocks, although that increase may take decades to materialize. However wildfire also results in large emissions that should be presumably factored out if it results from natural causes, but perhaps not if it results from human action. Regrowth following natural fires should clearly not be counted if the emissions were factored out and not counted. Globally and in certain regions, other effects of management change may be important. For example, subtle changes in fertilizer application, rotation lengths or fire management also contribute to overall C stock changes (Spiecker, 1999) but they have a smaller impact and are more difficult to measure at small scales than those of land-use change activities.

Legacies of past practices in forests as they affect age structures play a smaller role in afforestation, reforestation and deforestation (Article 3.3) because land-use change activities prior to 1990 are excluded by definition. However, legacies do play a role in determining site condition such as initial C stocks and nutrient status. Under Article 3.4, which includes management practices undertaken post-1990 in pre-1990 existing forests, there is the need to address ways to factor out the effect of skewed age-class structures on C sinks and sources.

The practice of net-net accounting or base period subtraction (by subtracting net greenhouse gas emissions during the base year, 1990) for cropland management, grazing land management, and revegetation activities under Article 3.4 of the Kyoto Protocol appears to lessen the need to develop methodologies to factor out systematic, long-tem indirect effects (they will likely cancel out since they were mostly happening before 1990) for these activities (IPCC 2002; Cowie et al., 2007).

Thus, factoring out presents the biggest challenge where land-use changes do not occur, i.e., croplands remaining croplands, grasslands remaining grasslands, and especially for forests remaining forests. As explained above, net-net accounting helps to factor out indirect and natural effects, to the extent that these are present both in the first and a subsequent accounting period. However, it provides little help in factoring out interannual variability, especially with a single base year (e.g., 1990), and may amplify problems if, for example, the single base year was affected by unusual climatic conditions (Cowie et al., 2007). It is worth noting that the new IPCC Guidelines for National Greenhouse Gas Inventories do allow for a change of the base line if it was unusually different (IPCC-AFOLU, 2006). The degree to which interannual variability will enter the estimates will not only depend on the length of accounting periods, but also on the measurement methods, whether they are real-time estimates for short periods (such as estimates from flux towers), or longer-term aggregators of effects, like soil or biomass inventories at two points in time. For example, greenhouse gas inventories that are based on estimating C stocks from forest inventories at two points in time implicitly factor out the interannual variability within the period between the two inventory times.

In the case of forest management, net-net accounting was not used in the Kyoto Protocol because of saturation concerns (Schlamadinger et al., 2007a). Gross-net accounting was considered, but it created at least two problems: i) windfall credits for countries with existing and ongoing sinks, and ii) the fact that indirect and natural effects are even more present than in net-net accounting. A gross-net accounting approach was finally adopted along with a proxy means to limit the impacts of indirect and natural effects: a negotiated cap on C stock changes. The value of the cap was based on the notion that about half of the stock changes are indirect and from natural causes, and of the direct human induced ones, about one third originated from forest management activities before 1990. The factor of one third is based on the assumption of an average 60-year rotation period in temperate and boreal forests, so that it would only be possible to do systematic management changes on about 1/3 of the land during a 20 year period. The factor of 2 and 3, if combined, resulted in the 15% cap[1].

In summary, the solutions used for the First Commitment Period, although useful for their high degree of simplicity, fall short of establishing a robust accounting system that maximizes fairness of credits and debits for human actions. There is therefore a need to develop methodologies for the second and subsequent commitment periods that can more effectively account for the direct human-induced influences on C sources and sinks and provide incentives to maximize the utilization of cost-effective greenhouse-gas mitigation options in the land-use sector.

4. Methodologies to factor out

This section presents accounting options for factoring out in a policy context (4.1 to 4.5) as well as other more science-based approaches (4.6 and 4.7) which might become policy relevant in the future in a tiered system. They are of different complexity and are able to factor out individual processes or groups of processes consistent with the overall framework described above. The various options deal to a different degree with the effects of i) interannual variability due to short-term precipitation and temperature changes, and disturbances, ii) long-term, more systematic indirect and natural effects (N deposition, CO_2 fertilization, long-term changes in precipitation and temperature), and iii) age-class effects. It would be possible to combine more than one of these options in support of the development of a factoring out framework for improved C accounting rules.

4.1. Selecting longer accounting or measurement periods

[1] An issue that may be unresolved relates to the symmetry of the approach, such as whether a 15% cap applies to C source as well as sinks from a country; see also:

One way of account for interannual variability is by choosing accounting periods (base period and commitment period) for Land Use, Land-Use Change and Forestry (LULUCF) that are long enough to minimize the impacts of interannual variability. In the case of net-net accounting, this should apply to both the base period and the commitment period. While longer accounting periods can integrate the impacts of interannual variability, other systematic effects like N or CO_2 fertilization can only be minimized if these longer periods are combined with net-net accounting (such as currently used in the First Commitment Period for cropland management and grazing land management). Even in the case of short accounting periods, it may in any case be more pragmatic to use longer measurement periods (e.g., 5 or 10 year intervals for forest inventories), which may lead to the equally practical outcome as the formal use of longer accounting periods.

4.2. Correcting national GHG inventory results for interannual variability

This includes the calculation of normalized inventory results that correct the measured forest inventory-derived stock changes for measured parameters subject to interannual variability, such as precipitation and temperature. Research is under way on feasible approaches to factor this out from an emissions inventory. This approach has not entered the UNFCCC inventory reporting. In this context, it should be mentioned that energy-related emissions also have some interannual variability, especially concerning hydropower and power demand for air conditioning and heating. In principle, such normalization could therefore also be applied to energy emissions estimates.

4.3. Factoring out through activity-based accounting

The use of C response curves (West et al., 2004) is another possible way of factoring out. It would involve monitoring of areas on which human activities are implemented to reduce emissions (such as areas converted to no-till agriculture) with C response curve generated for each specified activity. C response curves would be derived from general research and monitoring of specific sites rather than from large-scale monitoring. Obviously, the C response curve would need to be peer-reviewed or remain accessible for future inventories or other reviewers for checking. Models, driven by a number of external parameters, could also be used to derive the C response curves, as long as they are validated with site-specific data.

The use of activity-based accounting could be restricted to the activities of afforestation, reforestation, revegetation, and deforestation as the stock changes on these lands can be considered directly human induced. Beyond that, countries could be allowed to select other activities in the categories of crop land management, grazing land management, and forest management, provided that the activities can be tracked over time, and that the C response

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(http://www.joanneum.at/carboinvent/workshop/Master_Forest_policy_BOG_report1.pdf, page7).

curves are derived in a transparent and verifiable manner. It could also be made a requirement that any activities elected (such as conversion to no-till agriculture) would also have to include the reporting of any opposite activity (introduction of conventional-till agriculture).

This activity-based accounting could be used for cap-and-trade regimes, whereas for the purposes of UNFCCC reporting, one should continue to report the C stock changes and non-CO_2 GHG emissions on all managed lands, as prescribed in the 2006 IPCC Guidelines (AFOLU sector).

4.4. Factoring out through baseline scenarios or benchmarks

Another method at the project level is the setting of a dynamic baseline scenario. This can help to factor out systematic indirect effects to the extent that these are included in the baseline and will be responsible for part of estimated C stock changes. In managed forests, one could use a baseline for the future forest management sink or source based on an initial age-class distribution. This baseline could be derived by research in the country and would need to be reviewed and accepted internationally. This baseline value could be a function of some externally measured parameters, such as climate, occurrence of disturbances, fire, etc. The baseline would be adjusted ex post, depending on the number of natural fires or other identified disturbances or climatic anomalies in each year (Schlamadinger et al., 2007b).

4.5. Average C stocks approach

The Average Carbon Stocks (ACS) approach (Kirschbaum et al., 2001; Kirschbaum and Cowie, 2004; Cowie et al., 2007) has been developed to directly identify and quantify the human component of biospheric C stock changes and to provide a specific and practical means of assigning debits and/or credits for biospheric C exchanges due to direct human impacts.

The approach is based on estimating time-averaged C stocks under different land-use systems with the typical management practiced for that land use. While average C stocks vary between sites as a function of environmental factors such as climate and soil type, for a given site, average C stocks principally vary as a result of land use and management. Hence, as long as the land use and management regime remain the same, long term average C stocks remain the same, and therefore, by definition, no credits or debits accrue.

Realized C stock changes are then ignored as long as they do not reflect a change in long-term average C stocks. For example, if a fire or other natural disturbance occurs, or if a forest is still in the period of regrowth following a previous disturbance, these stock changes do not lead to debits or credits. Likewise, if a forest is logged as part of the normal forest rotation then the long-term average C stocks would not be affected so no debits or credits accrue. In contrast, if land use or management regimes are changed, then credits or debits accrue corresponding to the difference in average C stocks between the former and new land use or management regimes.

As average C stocks under given soil and environmental conditions can only change as a direct result of changes in land use/ management, an assessment of average C stocks and their changes provides a direct measure of the human effect on C stocks and thus directly relate to the assigning of debits or credits. No further factoring out is required.

The ACS approach also allows average C stocks within a land-use category to be adjusted. Such an adjustment may be deemed to be due to actions of relevant land holders, such as because of changing management regimes, and debits or credits will be assigned. Alternatively, the change in average C stocks may be due to factors beyond the control of land holders, such as climate change, in which case the adjustments are made without assigning credits or debits (Kirschbaum et al., 2001; Cowie et al., 2007). The approach requires a sufficient desegregation and repeated updating of average carbon stocks across a country to adequately account of any effects of environmental change or evolving management practice.

With approaches other than the ACS approach, all land areas need to be monitored to determine whether C stocks have changed (Fig. 2a). If there are no observed changes in C stocks on managed lands, no further action is needed until the next monitoring period. If there are changes in C stocks, it is required to undertake the difficult task of partitioning them into direct human induced and natural or indirect human induced components. A requirement of this approach is that the net balance of emissions and removals, including non-CO_2 greenhouse gas emissions, is calculated for all managed land areas and that the indirect human-induced and natural components are factored out. That is the essential and difficult task under approaches other than the ACS.

In contrast, under the ACS approach, the initial question is whether a land-use (or management) change has occurred (Fig. 2b). For most land areas, there would be no changes. For the small proportion of areas that have undergone a land-use change, it then becomes necessary to assign credits or debits based on the difference in average C stocks between the old and new land uses. If there are changes in average carbon stocks even without any causal change in land use or management, average carbon stocks need to have changed as a result of climate change or other global factors such as atmospheric nitrogen deposition. Average carbon stocks then need to be adjusted without assigning credits/debits so that any possible future change in land use/ management can be appropriately debited or credited.

Adoption of the ACS scheme would have the consequence that the majority of C stock changes in the countries with largest biosphere contribution to net C exchange would be excluded from accounting (Kirschbaum and Cowie, 2004). Only those C stock changes that are indeed the result of direct human action since 1990 would be included.

4.6. Terrestrial biospheric process models

The current generation of biospheric models are still largely confined to scientific approaches to addressing the issue of factoring out, and are still far from being ready for possible adoption in international treaties. However, in the future such methods could become the high-complexity end of a tiered system of factoring out of methodologies.

Biogeochemical process-based models are one of the important tools for factoring out multiple influences on C sinks and sources. Because of their structure and the processes that are usually taken into account, they are most suitable for factoring out natural (climate) and indirect-human influences (e.g., CO_2 and N fertilization). Most models of this type have limited capacity to deal with direct-human influences, although rapid progress is being made in incorporating human influences. Many process models deal with direct human influences as prescribed external drivers (McGuire et al., 2001) or with off-line model outputs (e.g., subtracting the effects of forest regrowth due to age structure by using simple demographics models based on forest inventory data; Caspersen et al. 2000).

Model development for such approaches requires the concomitant implementation of multi-factorial field experiments with control plots in order to inform model development and validation. Because models and experiments of this type are data intensive, they are less suitable for global applications. They can be very effective, however, at regional and local scales provided they can be properly parameterized. They are predictive and can simulate growth responses to a range of environmental changes.

The modeled partitioning of emissions and removals will be affected by the quality of the data used to constrain and test the models. Models cannot easily be transported to different environments from where they were developed, unless the appropriate testing and additional data collection take place.

Process models developed to account for the impacts of global change are constrained in their ability to contribute to factoring out because natural disturbances, management effects and land-use change are often poorly represented. On the other hand, models specifically developed for C accounting focus on management effects, land-use change and often also natural disturbances, but they are typically driven by empirical growth curves and are therefore also constrained in their ability to address factoring out issues (Kurz and Apps, 2006). Future model development should therefore focus on convergence of process-based and empirical models.

A recent application of a process model combined with forest inventories in a 0.5 Mha coniferous forest in Germany showed that over the last 20 years, only young and old stands were accumulating C with the combined indirect human-induced effects (CO_2 fertilization, N deposition, and climate change) responsible for 30% of biomass accumulation. This effect was largely driven by warming and N deposition on these high altitude forests for which both temperature and nutrients were growth-limiting factors (Vetter et al., 2005).

4.7. Combining forest inventories and demographic models

Other approaches have tried to estimate the C sink due to past legacy of land use change from that of indirect human-induced effects. A simple approach (although quite data intensive) is the one of comparing growth rates at different times for which we know that indirect effects were different, e.g., the increasing atmospheric CO_2 concentration over time. Caspersen et al. (2000) used forest inventories and a demographic model to estimate the effects of past legacies on forest biomass accumulation in the eastern USA, where the effect is believed to be important. Forest growth rates were calculated using 20,000 forest inventory plots for the periods of the late 1970s to mid 1980s and from the early to mid 1990s by estimating the changes in forest biomass due to growth and mortality based upon the age-class structure of each plot. They found that rapid forest regrowth (on areas where cropland was abandoned decades ago) was responsible for 98% of the biomass accumulation and that the residual was probably due to CO_2 and N fertilization. Given that the indirect effects were not measured but obtained as residual, Caspersen et al. (2000) did acknowledge that the effects could be larger, and that they may be counteracted by negative effects of other processes such as tropospheric ozone.

5. Conclusions

- Current terrestrial C sources and sinks are controlled by two major categories of processes: i) processes driven by atmospheric and climatic change and variability (including the effects of long- and short-term changes in precipitation and temperature on heterotrophic respiration, fire, increasing CO_2 concentration and N fertilization), and ii) processes driven by land-use change and management (e.g., forest age, forest thickening, woody encroachment, afforestation, reforestation, deforestation).
- Improved process attribution to current C sources and sinks is required to better understand future contributions of the terrestrial biosphere to atmospheric CO_2 growth.

- It will take a number of years before we have a global budget with adequate attribution of C quantities to specific processes. Current national, regional and global efforts to deploy C observatories combining *in situ* measurements (e.g., forest inventories, stand-level flux measurements) and remotely sensed measurements (e.g., land cover, greenness indices, etc.) need to be able to attribute specific C quantities to major underlying processes such as natural disturbance (fires, insects), land-use change and management. Other finer-resolution processes can be understood through bottom-up ecological studies including manipulative field experiments.
- For the purpose of C accounting for international GHG accounting policies, it is not necessary to factor out individual processes but it is sufficient to separate direct human-induced influences from the combined effects of natural and indirect human-induced influences. This is consistent with the Marrakesh Accords. The latter approach can be further developed and implemented to a large extent based upon current understanding and available tools, allowing the adoption of factoring out in GHGs accounting within the next 4 years of negotiations for the post-2012 regime.
- For land-use change activities (afforestation, reforestation, deforestation, cropland to grassland conversion or vice versa), factoring out may not be needed because the land-use change itself is a direct human action. For example, a human decision to reforest land will lead to C stock changes that will also be affected by some indirect and natural effects, but these would not have been effective without the human activity.
- The Kyoto Protocol rules for the First Commitment Period have avoided the need to factor out the legacies of past land-use change prior to the reference year 1990 by means of accounting rules. Article 3.3 directly defines human activities (afforestation, reforestation, and deforestation after 1990) and under Art 3.4 credits/debits for forest management are either restricted through adoption of specified allowable caps on emissions/removals, and those for other activities are determined by net-net accounting. Countries may also opt not to include Article 3.4 activities for the First Commitment Period at all.
- Even for short timeframes (e.g., 10 years), the impacts of interannual variability (e.g., drought) or natural disturbances (e.g., wildfire) may be large and methods will need to be developed to account for these natural or indirect human-induced impacts (if management of the biosphere is to be fully included in post 2012 greenhouse-gas emission control agreements).
- Under the Kyoto Protocol, factoring out poses the largest challenge for lands with elected management activities (Article 3.4 - grazing land management, cropland management, revegetation and forest management) because their area is typically much larger than that of lands subject to accounting under Article 3.3. Neither net-net accounting nor negotiated caps on forest management credits and debits adequately address the wide range of issues that

need to be considered in factoring out. Among those challenges are interannual climate variability (e.g., the European drought of 2003 and interannual variability in natural disturbances).

- Some of the methodologies presented in section 4 are relatively simple and deal with single factors or groups of factors. These methodologies are readily applicable, and are consistent with the request from the Marrakesh Accords. Options include: selecting longer accounting or measurement periods to reduce the effects of interannual variability; adjustment of national inventory results for inter-annual variability; use of activity-based accounting and C response curves; use of baseline scenarios or benchmarks at the national level; stratification of landscape into units with distinct average C stocks (average C stocks approach). Other, more sophisticated, modeling approaches (e.g., demographic models in combination with forest inventories; and process-based models) could be applied in the future, but are more data intensive, which makes adoption in an inclusive international C accounting system more difficult.
- Future development of factoring out approaches will benefit from the on-going convergence of empirical models focused on land-use change, natural disturbances and management, and process models focused on physiological responses to environmental changes.

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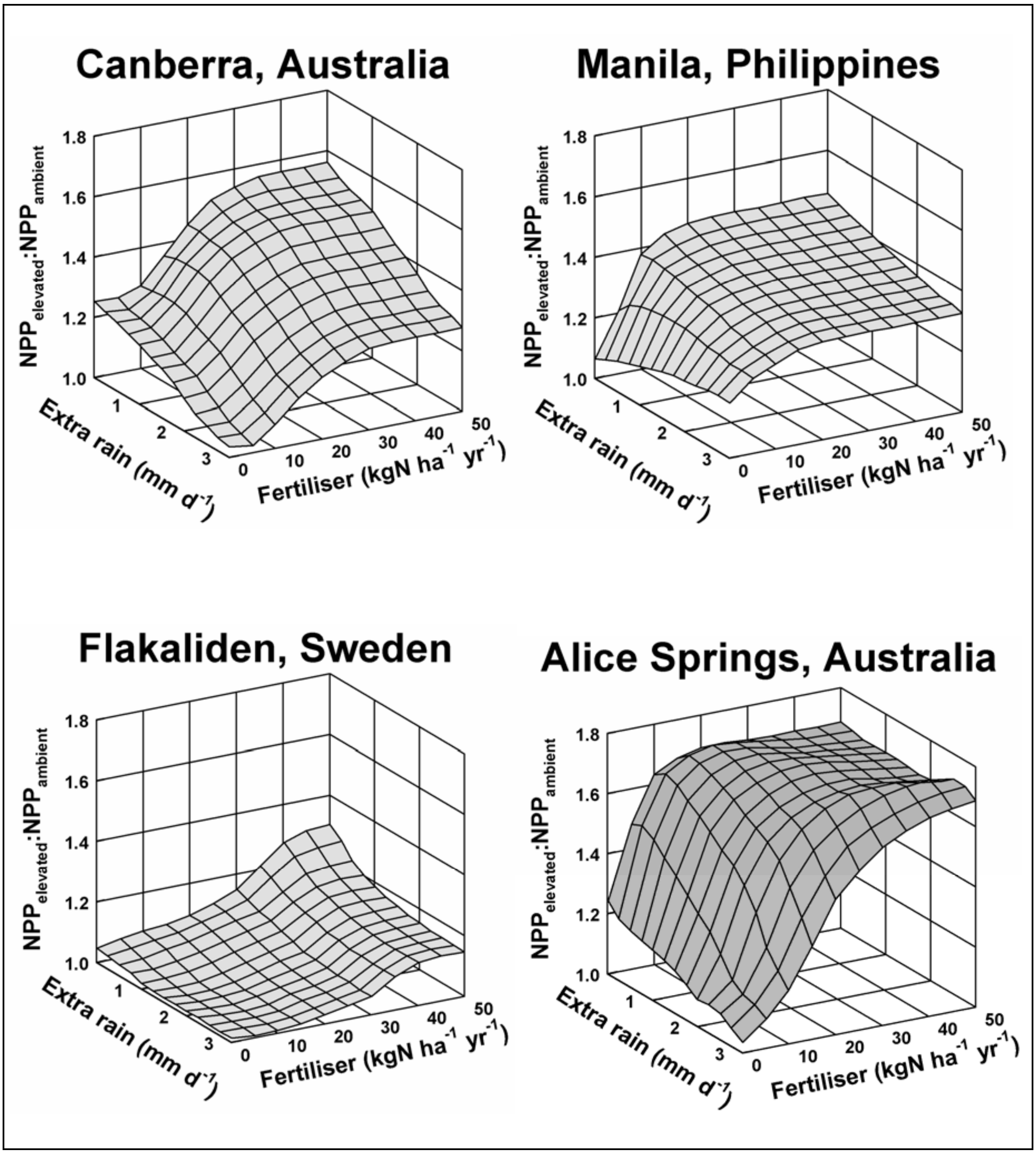

Figure 1: Forest NPP ratio at doubled and ambient CO_2 concentration for four different locations with contrasting environmental conditions (redrawn from Kirschbaum, 2004).

Figure 2. Flow diagram for the decision-making process under approaches other than the ACS to assign credit/debits (a), and under the ACS approach (b). ΔC is an observed change in carbon stocks and ΔACS a change in calculated average carbon stocks. 'Natural' in (a) includes factors such as age-class effects, CO_2 fertilization, climate change and nitrogen deposition, and 'human' refers only to direct-human induced causes. It makes the distinction between causes for which responsible landholders should receive credits or debits and those that are beyond their control. LUC in (b) is a change in land use or management.

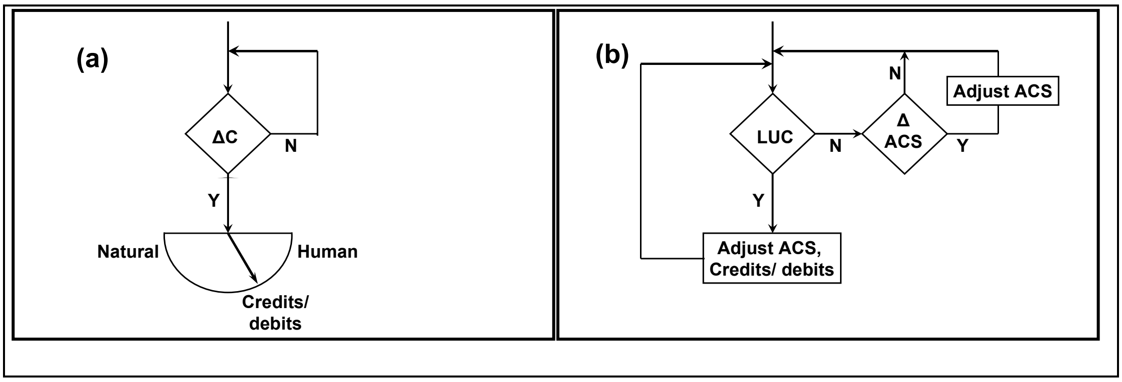

Table 1. Sink and source processes contributing to the net global C balance. This is based on a perturbation budget, i.e., it includes only fluxes that are altered by direct or indirect human–induced influences.

Sink and Source Processes	
Driven by atmospheric and climate variability and change	Driven by land-use change and management
• CO_2 fertilization • N Fertilization by N deposition • Plant growth suppression by air pollution • Changes in plant production due to climate change/variability • Changes in soil respiration due to climate change/variability • Natural disturbances (wildfire, insect attacks, cyclones) • Others such as vegetation shifts, global dimming, etc.	• Vegetation regrowth, thickening and encroachment • Afforestation and reforestation • Deforestation • Agricultural conversion, crop management and other land use changes affecting soil carbon • Erosion and C burial in water bodies • Others such as changes in harvest and fire cycles, etc.

Table 2. Feasibility of factoring out the main categories of source/sink processes and management practices. From easier to more difficult (*, **, ***)

Process	Factoring out feasibility	Sink (+)/source (-)
Natural Influences		
Climate Variability (e.g., El Nino, Pacific Decadal Oscillation, heat waves)	**	(+) or (-)
Natural disturbances (e.g., fire, insect attacks)	**	(-)
Indirect human-induced influences		
CO_2 fertilization[α]	***	(+)
N deposition[α]	***	(+) or (-)
Air pollutant effects (e.g., O_3, SO_2, heavy metals)	***	(-)
Long-term climate and variability trends due to GHGs forcing (e.g., length of growing season, permafrost thawing)	***	(+) or (-)
Disturbances associated with long-term climate and variability trends due to GHGs forcing (e.g., fire, insect attacks)	***	(-)
Management shifts (non-intentional for the purpose of C sequestration)	**	(+) or (-)
Direct human-induced influences		
Afforestation and reforestation	*	(+)
Deforestation	**	(-)
Forest management[β] (e.g., rotation, thinning, fire manag.)	*	(+)
Cropland management[β] (e.g., tillage, slash/burn, fertilization, rotation)	**	(+)
Grazing land management[β] (e.g., shelterbelts, weed manag., rotation, fertilization)	*	(+)
Revegetation	*	(+)
Past Legacies of Land Use and Land-Use Change (prior 1990)		
Age structure of forest[α]	**	(+)
Changes in soil C and nutrients	***	(+) or (-)

Footnote:

(α)indicates that the process is included in the definition of factoring out in the Marrakesh Accords.

(β) indicates that practices that can result in C sequestration or emissions but they are considered in this section as practices purposefully used to increase the net C sink.