IPCC MEETING ON CURRENT SCIENTIFIC UNDERSTANDING OF THE PROCESSES AFFECTING TERRESTRIAL CARBON STOCKS AND HUMAN INFLUENCES UPON THEM

SCIENCE STATEMENT

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Key Conclusions and Recommendations

The scientific community cannot currently provide a practicable methodology that would factor out direct human-induced effects from indirect human-induced and natural effects for any broad range of LULUCF activities and circumstances. Research efforts are addressing some particular effects, such as CO_2 fertilization, over a range of spatial scales and are providing information relevant to the separability and attribution of different effects at specific sites where good historical information is available and intensive measurements are being carried out. Such efforts are expected to provide an increasing understanding of the feasibility and practicability of a broadly based approach to the issues of separability and attribution.

In many circumstances the direct effects of ARD activities on carbon stocks and greenhouse gas emissions and removals will be much larger than the sum of indirect human-induced and natural effects, and the non-linear interactions among all effects. The scientific and technical community can provide guidance that will evolve and improve over time and offer rigorous approaches for such activities and particular timescales.

Following an initial LULUCF activity, indirect factors such as climate change and changing disturbance regimes are likely to grow in relative importance over time. These indirect human-induced and natural effects may either increase or decrease the change in carbon stocks that would have occurred due to direct human-induced activities in their absence.

Paired treatment and control plots offer a clear but limited potential to quantify the overall impact of management activities on a unit of land under current environmental conditions. Differences in carbon stocks and greenhouse gas emissions and removals between plots result not only from direct human-induced effects but also from the interactions with indirect human-induced effects, natural effects and past practices.

Control plot techniques, which are well developed in management contexts, by themselves do not allow a determination of the indirect and interaction effects. Thus they will be more appropriate to factoring out indirect human-induced and natural effects where direct management effects can be shown to dominate. This requires a suitable control plot strategy. For example, past practice effects on soils influence nutrient supply and growth, and can be highly variable spatially, setting requirements for control plot spacing. In the case of afforestation and reforestation, difficulties arise because control plots would not have trees growing on them but would be subject to revegetation influences from the surrounding managed landscape.

In general, plot-level controls provide little information about landscape-scale effects of management. The spatio–temporal dynamics of carbon stocks and the factors influencing these dynamics (such as past practices, disturbances, and age class structure) must be taken into account to scale-up stand-level information to the management area or country level for some Article 3.4 activities. For some purposes, spatio–temporal variability remains mainly a sampling problem. However, interactions among patches exist over a wide range of spatio–temporal scales and need to be taken into account in the scaling up of plot-level information.

Further progress in understanding and documenting disturbance regimes (e.g. fires, storms, insects and disease) that affect factoring out at the landscape scale is also needed. Quantification of the direct human effects on past and present disturbance regime changes has not yet been demonstrated at the spatial scales needed for analyses at landscape or country levels. It may not be possible with current techniques to factor out the interaction of changes in disturbance regimes from other effects on carbon fluxes.

The scientific community has surprisingly little experience in attempting to factor out all of the effects causing observed changes in carbon, because the recent focus of carbon science has been on quantifying fluxes rather than on attributing them to mechanisms. The non-linear and non-additive effects of past practices, of nutrient feedbacks (CO_2 and nitrogen), and of changes in climate, pollutants, aerosols, and invasive species complicate the quantification of direct effects in isolation. Their mutual interactions and their interactions with direct human-induced effects on carbon stocks and greenhouse gas emissions and removals add further complications to quantification. Some of the effects on terrestrial stocks are highly non-linear and it may be impractical to separate these factors, in particular CO_2 and N-fertilization feedbacks which can become strongly non-linear in combination. Such non-linear interaction terms, together with their different time scales of the responses, add uncertainties and complicate factoring out.

Pilot or demonstration research projects attempting factoring out for specific regions and projects would be extremely useful in quantifying currently achievable accuracy and completeness. Explanation of observed net fluxes in terms of component processes is necessary to meet the requirements for full factoring out of direct effects relative to indirect and past practice effects. This is an essential first step towards outlining methodologies that would be both practicable and verifiable. There is a strong science foundation for taking this step, which could help to quantify the uncertainties associated with poorly understood interactions.

Advances in developing a better understanding of the interactions between different effects in a broad range of circumstances could be assisted through improved access to relevant datasets and coordination of data quality and data archiving. This applies to a wide range of required data, including that for land management practices, land-cover changes, information on disturbances, and air-quality.

Top-down assessments, based on atmospheric measurements and verified process-level understanding, have the potential to identify carbon stock changes and greenhouse gas emissions and removals on the scale of continents and large countries. This, in combination with bottom-up approaches and appropriate methodological development, could lead to a verifiable budget and attribution scheme. Uncertainty in the magnitude of tropical deforestation is a key issue presently limiting this approach for some regions. It will take at least one to two decades until the science community can offer an integrated, network-based approach for the accounting of carbon stock changes and their attribution to direct human-induced and other effects on a country level. To reach this goal will require a significant investment, coordination and an international research effort. Such an approach fully realized, together with accurate models, would allow evaluation of bottom-up attribution estimates against regional checks.

Future progress depends on a combination of different approaches and their integration. Among the approaches are satellite remote sensing products, development of appropriate economic indicators, flux measurement technologies, and a wide variety of high-technology measurements (e.g. FACE or isotopic measurements). Integration of inventory measurements, measurements that capture forest and agricultural product streams, and model-data integration are expected to become more important. An enhancement of understanding at the process level is crucial to overcome the limitations of the current model and measurement approach hierarchy.

1. Introduction

The goal of this expert meeting was to survey the scientific understanding of carbon cycle processes that are relevant to a request by SBSTA that the IPCC consider

> *"…(the development of)… practicable methodologies to factor out direct human-induced changes in carbon stocks and greenhouse gas emissions by sources and removals by sinks from changes in carbon 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 fertilization and nitrogen deposition), and effects due to past practices in forests"*(Decision 11/CP.7, Marrakech Accords, FCCC/CP/2001/13/Add.1).

In particular, the desired methodologies need to address the requirement

> *"That accounting excludes removals (of carbon dioxide from the atmosphere) resulting from (i) elevated carbon dioxide concentrations above their preindustrial level, (ii) indirect nitrogen deposition, and (iii) the dynamic effects of age structure resulting from activities and practices before the reference year."* (Draft Decision -/CMP.1, Marrakech Accords, FCCC/CP/2001/13/Add. 1).

This request represents a significant challenge to carbon science because of the existence of multiple indirect effects and complex interactions between direct and indirect effects and with past practices.

Terrestrial carbon stocks occur in a variety of biochemical and structural forms and in a wide range of environments. Most of these stocks are currently responding at different rates to changes in past and current land management and environmental factors. The aggregate result of such stock changes in recent decades has been to cause a net removal of CO_2 from the atmosphere to the terrestrial biosphere at a rate that is highly variable from year to year (WG1-TAR, 2001). The decadal average values of this uptake have been estimated at 2.3 ± 1.3 $GtCyr^{-1}$ (SRLUCF, 2000, for 1989-1998) and 1.4 ± 0.7 $GtCy^{-1}$ (WG1-TAR, 2001, for 1990s). Such uptake, and its variability, are large relative to the reduction commitments implied by the Kyoto Protocol.

Processes that may be contributing to recent net removal include:

- *Increasing net primary productivity*: e.g., extended growing season, CO_2 fertilization, nitrogen fertilization, improved plant varieties, improved land management, and biological invasions.
- *Recovery from past disturbances*: e.g., regrowth on previously harvested or burned forest land and carbon recovery in agricultural soils.
- *Decreases in disturbance*: e.g., fire suppression and pest control.
- *Extending turnover time*: e.g., establishing a new forest.
- *Other processes*: e.g., sediment burial in reservoirs, landfills, and storage in long lived wood products.

The relative importance of these contributing processes varies between regions and, within a region, may vary over time. Furthermore, the partitioning of net uptake among these processes is not known quantitatively. This is because the individual changes that must be separated and measured are small signals against large background variations, and the processes driving those fluxes are known to interact in ways that are not necessarily strictly additive.

In addition to processes contributing to carbon uptake, there are a number of fluxes and processes that contribute to carbon emissions and that must be considered in estimating the net carbon flux between the terrestrial biosphere and the atmosphere. For example, recent new research suggests that carbon sources associated with tropical deforestation may lie towards the low end of the range presented in the WG1-TAR. If true, this would imply that a smaller net terrestrial sink is needed to close the global budget than originally thought. It may also imply a reduced margin to manage the carbon cycle with land-based strategies where such activities seek to restore previous carbon stocks.

In order to consider the feasibility of the more specific attribution required to address the issue of “factoring out”, the workshop considered the following inter-related topics:

- Separability: Do processes combine additively in an arithmetic sense, so that they may be separated, or are there non-additive and nonlinear interactions between processes which may make separation difficult or practically impossible?
- Permanence: Is carbon, once stored, sequestered in long-lived fractions (either natural reservoirs or terrestrial carbon products) or in short-lived forms that are likely to re-enter the atmosphere in the near term?
- Saturation: Are there internal carbon-cycle processes that limit the amount of carbon that may be stored in the various carbon compartments?
- Stability: How variable or changeable are the carbon stocks due to variations (e.g. ENSO variability in climate) or trends (e.g., trends in temperature or surface ozone) in forcing?
- Attribution: What approaches, including but not limited to measurements, experimental manipulations and models, may be used, assuming separability is possible, to separately quantify direct, indirect and past practice effects?

1.1 A framework for identifying effects and their interactions

A framework for approaching the “factoring out” problem and its interaction with land-use and management effects at site, project or management area levels was developed during the workshop based on the following 2-way factorial analysis of the problem:

	Natural State	With Indirect Effects
Unmanaged System	Case A	Case B
Managed System	Case C	Case D

Case A may be thought of as the ‘control’ situation where both land management effects and indirect effects are absent. The transition from A to C is the effect of land-use change and management, independent of any indirect effects. The transition from A to B is the effect of indirect effects on the system in the absence of management. Finally, the transition A to D is the effect of both management and indirect effects including their interactions.

A strict interpretation of the language of the Marrakech Accords would require identification of the change in carbon stocks caused by management in the absence of indirect effects — that is, the difference between cases C and A above. In reality, observations and analyses provide direct information only on the difference between cases D and B above. The effect of management may be modified in the presence of indirect effects, so the differences (C – A) and (D – B) may not be equivalent. The different types of effect that might be identified within this framework are:

Result of management under the influence of indirect effects	D – B
Result of management on an unmodified natural system	C – A
Result of indirect effects on an unmanaged system	B – A
Result of indirect effects on a managed system	D – C
Result of management plus indirect effects and their interactions	D – A

If the interactions are antagonistic, then (C – A) > (D – B), whereas if the interactions are synergistic, then (C – A) < (D – B).

The challenge of factoring out thus requires not only a determination of the changes in carbon stocks caused by the management activity of interest (D – B), but also of the results of indirect effects on both managed and unmanaged systems, i.e. (D – C) and (B – A), and their interaction (D – A). A critical question is the relative magnitude of these additional terms.

This factorial approach can also be applied to evaluate methods where the footprint of the method (e.g. eddy covariance, atmospheric budgeting, or inventory methods) includes both natural and managed landscapes.

2. Workshop Conclusions Regarding Previous Relevant IPCC Assessments

The following key findings of the SRLUCF regarding separation and attribution of changes in carbon stocks and greenhouse gas emissions remain valid and are elaborated further below.

> (SPM paragraph 44): *The Kyoto Protocol specifies that accounting under Article 3.3. be restricted to 'direct human-induced land-use change and forestry activities, limited to afforestation, reforestation and deforestation' occurring since 1990. For activities that involve land-use changes (e.g. from grassland/pasture to forest) it may be very difficult, if not impossible, to distinguish with present scientific tools that portion of the observed stock change that is directly human-induced from that portion that is caused by indirect and natural factors*.
>
> (SPM paragraph 45): *For those activities where only narrowly defined management changes under Article 3.4 are involved (e.g. conservation tillage) and the land-use remains the same, it may be feasible to factor out partially*

natural variability and indirect effects. Experimental manipulation or paired plots can be used for this purpose, but they are likely to be expensive to apply over large areas.

Projected changes given in the WG1 TAR are large for many variables, including CO_2, aerosols, ozone, and other atmospheric constituents that influence terrestrial carbon stocks and greenhouse gas emissions from land. These ongoing changes will have an increasing impact on our ability to develop practicable methodologies to factor out direct human-induced from indirect human-induced and natural changes in carbon stocks and greenhouse gas emissions.

The WG1 TAR also addressed the global-scale issues of permanence and reversibility of carbon stock changes. There is scope for land-use changes to increase or decrease CO_2 concentrations. The potential to increase atmospheric CO_2 by deforestation and other land-use changes is larger than the potential to reduce atmospheric CO_2 over the century through land-use changes. Hypothetically, if all of the carbon released by historical land-use changes could be restored to the terrestrial biosphere over the course of the century (e.g., by reforestation), 200 GtC would be sequestered. On the other hand, complete conversion of forests to climatically equivalent grassland could theoretically release 400 to 800 GtC.

3. Separability

> The topic of separability addresses how processes combine and whether combinations may be additive, synergistic or antagonistic. For example, non-linearities, feedbacks, and multiple limiting control factors may make separation of the individual effects of different processes difficult or practically impossible.

In the context posed by the Marrakech Accords it is only necessary to separate direct human-induced effects from the sum of indirect human-induced and natural effects. However, model-based approaches using simulation of identifiable processes will generally require some ability to separate among the various indirect human-induced and natural processes. Verification of the required separation will require at least the identification and quantification of the dominant indirect human-induced or natural effects.

Net carbon uptake is the imbalance between counteracting processes of uptake (photosynthesis) and release (respiration, combustion, and oxidation). Separating causal factors responsible for net changes in carbon stocks requires analysis and data for processes operating on a range of spatial and temporal scales, taking into account potential timing delays between the uptake and release mechanisms that may not occur at the same point in space.

Direct human-induced effects can be increased or decreased by indirect and natural effects, either because of those effects or because of their interactions with direct effects.

Whereas some processes combine in a simple fashion (additively), others are interactive due to non-linearities in eco-physiological processes. This is the case when LUC or climate change leads to qualitative changes in physiological or soil constraints on NPP and heterotrophic respiration. In this regard land-use change does often lead to qualitative change in the nature of soil nutrient and hydrological constraints on NPP and NEP.

In the case of forest systems the strength of a number of indirect effects also depends on the age of the stand or system, allowing for complex interactions of indirect and past practice effects with direct effects. For example, there is evidence that younger re-growing forests are more responsive to the CO_2-fertilization effect than mature slow-growing forests.

Present observing networks focus on regional estimates of carbon sources and sinks or carbon stocks and are not globally comprehensive. At the present time, they are not systematically aimed at separating the causal factors underlying these estimates. A broad portfolio of approaches will be needed to address changes in net carbon storage and their separation and attribution into underlying mechanisms. Careful process studies, multi-factorial experiments, innovative observations, and use or enhancement of operational long-term data are needed to address separation rigorously. Observing networks and supporting research studies are better developed for CO_2 than for non-CO_2 greenhouse gases. Thus addressing the corresponding issues of separation and attribution of changes in non-CO_2 greenhouse gas emissions and removals will also require extension of existing research programs.

Mechanistic models of ecosystem carbon dynamics, including soil nutrient feedbacks and interactions with the hydrological cycle, supported by suites of data, can provide a predictive understanding of changes in ecosystem-level soil-carbon stocks in response to land-use change and climate change. Studies using mechanistic models including soil nutrient feedbacks and their interactions with the hydrological cycle complement direct experimental tests and treatment-control plots. However, model-based approaches continue to have limitations because of inadequate scientific understanding of several key processes in carbon, nutrient and water cycling in ecosystems.

In general, carbon-stock changes and NEP responses to major land-use changes over small time and space scales, such as forest to pasture conversion, are greater than responses to temperature and, possibly, other climatically induced changes. At larger time and space scales, indirect and natural effects are more likely to be significant and are not necessarily strictly additive to direct effects. Simulations of land-use change and temperature effects based on an equilibrium model provide some evidence that effects on NEP can be numerically separated. Such studies will need to be tested in a wider range of circumstances, and equilibrium models will need to be replaced with dynamic ones to avoid errors due to equilibrium assumptions. Separability of causes associated with smaller changes in land cover or land-use practices over large areas will involve landscape-scale processes to a greater extent, and presents additional challenges.

4. Permanence

The topic of permanence addresses the lifetimes of carbon in different reservoirs and the factors that control partitioning of carbon among these reservoirs. A closely related issue is that of reversibility, which considers asymmetry between the rates at which a carbon stock might be increased or decreased.

Carbon cycles through different reservoirs in terrestrial ecosystems and the mean residence times in these reservoirs range from hours to millennia. Some of the carbon that leaves reservoirs is released back into the atmosphere while other carbon is transferred to other reservoirs, e.g. through litterfall from biomass to dead organic matter.

The permanence of carbon stocks is highly scale dependent. Within a stand, individual trees are regenerating while others are dying and releasing carbon back to the atmosphere. Although the carbonstorage duration in an individual tree may be limited, the storage at the stand level may be much longer. Similarly, within a forest management area, some stands will take up carbon while others will release carbon following harvest or natural disturbances. The duration of carbon storage should be assessed at the stand or at the landscape scale, recognising that at lower scales in the hierarchy (trees or stands) mean-residence times will always be shorter. Moreover the same carbon density (carbon per unit area) can be achieved through storage in reservoirs with fast or slow turnover times.

A distinction must be drawn between the duration of sinks (how long annual removals of carbon from the atmosphere can continue) and permanence of storage. Changes in management regimes, such as the conversion from till to no-till agriculture or lengthening the harvest rotation in a forest management area, can result in a temporary sink, as the system adjusts to the change in management. Although this sink will eventually saturate, storage of the additional carbon that was removed from the atmosphere persists until such time as new management or changes in indirect effects bring about carbon releases.

Direct and indirect effects can influence the permanence of carbon stocks by modifying the relative distribution of carbon among different biomass and dead organic matter reservoirs. Direct human activities can result in the creation of long-lived forest product reservoirs, such as houses and landfills. The conversion of a forest with long-lived trees and dead organic matter reservoirs to agricultural land not only reduces the reservoir sizes, but also affects the permanence of future carbon storage as perennial trees are replaced by an annual crop, and large dead organic matter reservoirs are replaced by reservoirs with much faster turnover rates.

At the landscape scale, the age-class structure of forest stands affects the present and future carbon balance because the mechanisms involved in net carbon uptake and in plant responses to direct and indirect effects are age dependent. Present age-class distributions and carbon-stock levels are determined by the history of past practices and past natural and indirect effects.

The size and composition of ecosystem carbon reservoirs represent a memory of past events and vegetation types. Reservoirs with long residence times, such as coarse woody debris, soil carbon or forest trees, have a much longer memory than short-lived reservoirs, such as annual vegetation types. The impacts of past practices thus differ between reservoirs (biomass or soil), between ecosystem types (forests, grassland, or cropland) and between regions (tropical or boreal).

Carbon stocks in ecosystems are not permanent on a geologic time scale, in contrast to fossil fuels left in the ground. Fossil-fuel carbon emitted to the atmosphere becomes part of an active biogeochemical cycle. Although some may be taken up by ecosystems, terrestrial storage is affected by anthropogenic activities. This carbon remains potentially vulnerable to future release, possibly rapidly, to the atmosphere. Thus, in the long term there is a fundamental difference between avoided fossil emissions and storage in ecosystems. In the short term (years to decades), the net effect on the atmosphere of avoided emission and terrestrial uptake is the same.

Uptake and release processes (gains and losses) can be asymmetrical in time. Catastrophic losses can be followed by decadal or longer recovery periods. In some cases, rapid growth may be followed by prolonged degradation. Carbon stocks in frozen soils and wetlands, which have accumulated over centuries or millennia as a result of natural processes, are vulnerable to releases due to changing environmental forcing (e.g., warming or changes in the water table). Because of the large areas involved, such responses to indirect or natural effects could result in potentially large emissions.

5. Saturation

The topic of saturation addresses both the maximum storage of a site or region and the fact that responses to some environmental changes may only continue up to a point, such as a maximum CO_2 concentration or level of nitrogen addition. This topic includes consideration of the potential for present day carbon sinks to diminish or to reverse in sign due to a reduction in storage capacity.

The maximum carbon storage capacity or potential of a site depends on climate, CO_2 , nutrients, soil type and properties, species composition, and topography. Changing these conditions will result in a change in carbon stocks over some time scale. Saturation occurs when the increase or decrease in a stock or stocks through time goes to zero and a landscape reaches its maximum carbon density (mass per unit land area). In some cases this may be approximated by the carbon density of intact primary vegetation that occupied the landscape prior to human occupation in the absence of disturbance. However, if the new landscape has altered climate, nutrient inputs, species or other conditions, the new saturation level may deviate from the primary vegetation state in either a positive or negative direction. The carbon density of natural systems provides guidance regarding carbon storage capacity under past conditions mainly in productive forest regions (where very high biomass levels are reached) and provides substantially less information where climate or management may change the basic vegetation type (grassland to forest).

Saturation implies that the time-average carbon density of the landscape is stable on multi-year timescales. The current level of carbon stocks at a site, the storage capacity of the site, and the rate of carbon sequestration by vegetation and soils (dC/dt) determine the time to saturation, which may be very long for some systems. In some landscapes, especially peatlands, accumulation may occur over many millennia and the upper bound may be difficult to determine. Large spatial variability in carbon reservoirs and processes is a feature of all biomes from tropical forests to deserts. To accurately quantify saturation for ecosystems requires sufficient sampling in time and space to overcome variability and long timescale issues. Current knowledge of global biomes is limited by data availability and in some cases we do not understand the processes limiting maximum accumulation rates.

Land-use and management history can affect permanence by altering the structure and function of processes governing carbon dynamics of landscapes, such as biogeochemical cycles, biodiversity, hydrology and disturbance regimes. These processes play an important role in determining the time to reach carbon saturation and the saturation level.

Some specific processes governing sink mechanisms also saturate at critical levels of environmental variables. CO_2 fertilization declines to zero with increases beyond some critical atmospheric concentration, although the mechanisms causing saturation of the CO_2 effect in whole ecosystems remain controversial. Nitrogen saturation of mid-latitude northern hemisphere forested ecosystems typically occurs when nitrogen deposition reaches 10–30 kgN/ha/yr. Nitrogen saturation leads to nitrogen leaching from ecosystems and reduced responses to increasing nitrogen availability. The level may be different for other types of ecosystems. This, and the impact of nitrogen saturation on the carbon cycle, are not adequately represented in contemporary coupled terrestrial-carbon and nitrogen-cycle models. Current knowledge suggests that carbon and nitrogen saturation are inter-related because CO_2 fertilization can become nitrogen limited.

Different vegetation types with similar carbon saturation levels may allocate carbon differently among organic reservoirs. These reservoirs will have different characteristic turnover times. Hence, the rate of C-sequestration and time to saturation may differ among vegetation types even though the processes in these systems (CO_2 and nitrogen sensitivity) may have similar dynamics.

6. Stability

The topic of stability addresses the response of systems to trends and variability in the forcing factors. For example, changes in NEP are related to ENSO variations in climate as well as to longer-term trends in climate factors (e.g. growing season length) and pollution (e.g. ozone).

Trends and variability in the global environment cause changes in carbon fluxes that may mask, interact with or alter trends. For example, changes in temperature and rainfall with ENSO can cause very large year-to-year variations in carbon exchange rates. Other factors, such as the impact of nutrient or toxic deposition, may change rapidly in the future compared to the levels experienced over the course of past research and operational observation periods. Understanding how these volatile forcing factors affect carbon is thus key to separation.

With respect to climate, global models suggest that in the absence of significant land-use change and disturbance, carbon sinks will become carbon sources if the fractional rate of increase of specific respiration exceeds the fractional rate of increase of GPP. Respiration is expected to increase with temperature, and will therefore tend to increase with CO_2 concentrations at a rate dependent on the sensitivity of respiration to temperature and the climate sensitivity to CO_2. However, the sensitivities of respiration and carbon uptake to temperature and other environmental controls are highly nonlinear and are still the subject of much debate in the scientific community. In addition respiration is dependent on soil moisture, which is expected to change in regionally dependent ways.

The magnitude of GPP responses depends on the mechanisms responsible for its enhancement or reduction, and on other changes to interactive environmental factors, such as CO_2, nutrient and toxic deposition, and solar radiation. For example, O_3 exposure has been found to damage plant cuticles, although the full effect on plant growth is still an area of active research. Nitrogen availability changes with warming and can cause complex responses in GPP to climate variability. The nitrogen fertilisation effect may saturate at high anthropogenic nitrogen-deposition rates, leading to non-linear responses to nitrogen additions. Effects of the ratio of diffuse to direct radiation on photosynthesis will depend on cloud cover, future aerosol concentrations, and the mix of types of aerosols.

Nutrient and toxic deposition is an emerging issue, and may become even more critical to the issue of stability in the future. Major anthropogenic perturbations to the nitrogen cycle are evident in many ways, e.g. in the rapid rise of atmospheric N_2O concentrations. There has been more than a 5-fold increase in nitrogen deposition in the mid-latitudes of the northern hemisphere over last 100 years, and it has been 3 times higher in Western Europe than in the contiguous US. The dry-deposition portion of the nitrogen deposition budget is the most uncertain component. The ability of current 3-D chemical transport models to adequately simulate nitrogen deposition at global and regional scales is limited.

The coupling of nitrogen deposition to the carbon cycle is not yet fully understood (including the process of nitrogen saturation) and consequently it is not adequately represented or even included in current models. The non-linearity of nitrogen responses needs to be included in both models and experimental procedures, and interactions between nitrogen effects and pollutant feedbacks on carbon uptake may be of growing importance. These interactions and their non-linearities are not adequately considered in current measurement and modeling studies. Studies of the combined effect of air quality, nitrogen, elevated CO_2 and carbon cycling are needed before we can answer the inter-related questions of separability, attribution and stability in the growing number of regions affected by changing atmospheric chemistry.

7. Attribution

> The topic of attribution addresses the availability of measurement and analysis techniques to quantify components of observed fluxes that are due to separable processes. For example, are there existing or foreseeable approaches that can separate direct human effects from the sum of indirect and past practice effects over policy-relevant spatial scales?

Existing approaches that can contribute to attribution include inferences from the existing global integrated network of concentration observations, flux measurements, process studies, experimental manipulations, and treatment and control plots in managed lands, land-use and forest inventories, and remotely sensed data. As noted in section 1, it is important to distinguish between measurements of fluxes, or of carbon stock changes, and the separation and quantification of the contributing processes.

The available approaches have different spatial and temporal characteristics that make them relevant to different direct, indirect or natural effects and no single approach can be regarded as comprehensive by itself. There is a need to develop from current capability of detecting indirect effects as a residual term in the carbon budget, to a future capacity of measuring indirect effects proximally. To rigorously attribute causal mechanisms to the observed changes, a combination of approaches will be required that bring together disparate data sets, experimental observations and sound theoretical models.

Attribution at the site or ecosystem level based on process studies is complicated by ecosystem responses to multiple factors, as most sites are affected by multiple direct, indirect and past practice effects, such as simultaneous CO_2, nitrogen deposition and land-use history effects. It is currently possible to attribute changes in NEP and some other component fluxes to disturbance effects and to climate changes (precipitation, snowpack size, summer temperatures, growing season change, and cloudiness). Separation of CO_2 and nitrogen effects is more difficult. Coordination of ecosystem-process models and measurements can help to refine attribution, but some processes are not yet well enough understood for this combined approach to work. Thus further experiments with deliberate manipulation of nitrogen and CO_2 levels may be required to parameterize process models.

At the global scale, changes in the terrestrial flux of carbon in the 1990s can be tentatively attributed to a set of processes and interactions that includes recovery from past practices and some degree of CO_2 and nitrogen fertilization of growth. Quantification of the relative importance of different processes is in its early stages. For example, new studies are only beginning to account for major recent land-use changes in the former Soviet Union and Eastern Block Countries.

Land-use change includes a large number of activities and processes. Refinement and standardization of current methodologies and development of approaches for currently unmonitored lands will help to improve understanding of LULUCF effects on carbon stocks. Comparison of inventory estimates and carbon-flux changes with other approaches (such as inverse modelling) is complicated by the fact that each method includes different areas, reservoirs and processes within these areas.

A pilot study has investigated the combined use of atmospheric concentration measurements, ecosystem models, and inventory data to provide upper bounds on CO_2 fertilization effects in the tropics, Europe and Siberia. These estimates, derived in part from global observations, provide an important comparison to other estimates from analyses of processes and age-class distributions. Attribution to multiple factors at such regional to global scales is needed to understand the causal mechanisms underlying the observed changes and as a basis for prediction of future carbon–climate interactions. At the project and local scales, however, this approach presently provides relatively little guidance.

8. Synthesis - Time Scales

The carbon balance of terrestrial ecosystems depends on the dynamics of linked carbon reservoirs and the fluxes of carbon between these reservoirs. These fluxes occur over a broad range of timescales. Some component fluxes (e.g. photosynthesis and respiration) change almost instantaneously in response to environmental stimuli (e.g. changes in light level and temperature). They also interact with carbon reservoirs (e.g. leaf biomass and soil organic matter), which generally change more slowly (months-centuries), except when major disturbances occur (fire, major storm damage, harvest, etc.).

Practicable techniques for attribution would therefore need to consider the multiple timescales of response. Generally, impacts of indirect effects are most directly deduced from process studies and experiments (which tend to capture relatively fast processes), while effects of past practices and direct management are often estimated from forest, rangeland and crop–soil inventory-type data. For full attribution, these families of approaches will need to become well integrated.

Many of the non-linear and non-additive interactions among direct, indirect, and past practice effects occur when processes operating on different timescales interact. Carbon-cycle processes with multiple timescales of response generate transients (including possible non-monotonic changes) in response to a perturbation even in the absence of time-varying indirect effects (e.g fire and regrowth). Net land-atmosphere carbon exchange displays large temporal variability, especially in response to climatic anomalies (e.g. ENSO and volcanic eruptions). This means that the measurement period for a carbon sink must be long enough to allow separation of direct management effects from the ‘noise’ due to natural variability. The timescales associated with land-management and disturbances determine the age-class distribution of a forest and will therefore influence its sink strength. Age-class distributions may also influence the impacts of indirect effects (e.g. where CO_2 fertilisation acts preferentially on young plants), which would tend to confound land management effects and indirect effects.

Carbon accumulation in an aggrading (young) forest stand is large, relative to the potential accumulation due to indirect effects on the growth of individual trees, including climate, CO_2 and nitrogen. Changes in the rate or type of natural and human-induced disturbances alter both the carbon stocks and the forest age-class structure. Hence, at the landscape scale, changes in the rate of harvesting, storm damage, wildfires or insect outbreaks have the potential to account for large amounts of carbon accumulation (or loss) relative to impacts of other indirect effects on the growth of individual trees.

9. Synthesis - Space Scales

Characteristics of carbon stocks (permanence, saturation, and stability) and their drivers vary along a broad range of spatial scales. Drivers of carbon cycling range from local effects of individual species, soil texture, landscape position, and human impact, to global climate patterns. The relative importance of different drivers depends on the scale of interest. For example, if we are interested in estimating carbon stock changes at the 1-m scale, in semiarid ecosystems, presence of shrub or grass species is the dominant driver while climatic patterns could be considered as constant. If, on the other hand, we are interested in carbon stock patterns at the biome scale, these will be mostly determined at a given time by climate, parent material, and disturbance history, whereas the influence of individual plant species would be averaged out and less important.

Patches or stands may or may not interact depending on the landscape processes, carbon characteristics and time scale of interest. For some purposes, spatial variability represents mainly a logistical challenge and a sampling problem. When carbon patches do interact, for example when carbon stocks of a patch depend on the carbon stock of adjacent patches, it is necessary to explicitly describe the spatial interaction. Examples of this include the role of landscape structure in controlling wildfire patterns, contagion with insects and storage of eroded soil carbon in depositional sites.

Direct human-induced activities (ARD, Forest, Cropland and Grassland management) occur within a range of intermediate scales from landscape units, paddocks, to small political units, counties, and states. Humans do not typically manage at the meter scale and do not manage biomes as intact units. Effects of direct human-induced activities at the stand or site level are in most cases amenable to experimentation although the time scales of the experiments may need to be long. Human effects at the landscape level (e.g., fire management and erosion control) are more difficult to assess. The scales of information needed by decision makers generally differ from those most accessible to direct measurement, so that downscaling and upscaling introduce uncertainties in providing policy-relevant information.

Although direct human-induced effects occur over intermediate and decadal time scales, longer term (> 50 to 100 yr) trends in land-management activities may lead to changes in biome types (e.g. from forest to a mosaic of agriculture and settlements with fragments of forest) or to disappearance of certain biomes (e.g. desertification).

Indirect human-induced activities occur at all scales, from modification of the stomatal behavior to global-mean temperature. It is more difficult to assess the effects of indirect than direct human-induced activities in part because manipulative experiments are easiest at small scales. It is more practicable to separate direct effects from indirect effects plus effects of past practices than it is to separate among the indirect effects. Removing past practice effects requires knowing the state of the ecosystem in the designated baseline year. There are substantial uncertainties in establishing past ecosystem states that are needed for both ‘bottom-up’ and regionalized ‘top-down’ approaches. Estimates of these uncertainties have not been pursued systematically but models and estimation procedures are known to be sensitive to the initial states assumed. Important processes are missed in the carbon biogeochemistry models with our current initialization approaches. Past conditions and practices and the possible range in them are not adequately represented. We do not generally know the extent to which these factors determine the overall trajectory of the system and hence attribution.

10. Research Needs

Further progress towards resolving the issues raised in this report will require consideration of the following needs. A framework for integrated observations, experimentation and modelling that spans human activities is necessary to address attribution of indirect and direct effects at relevant temporal and spatial scales. Existing measurement networks cover a range of spatial and temporal scales, but do not provide the comprehensive global coverage needed. For example, inventories have timescales of repeat measurements > 5y, whole ecosystem and component fluxes cover daily to seasonal measurements of NEP and have generally been measured for < 10 y. However, gaps in available observational data for many processes, regions and time-scales must be filled.

In the near term, further synthesis of existing knowledge through expert workshops, and application of this knowledge to pilot projects aimed at developing preliminary methods and estimates of the relative contribution of direct and the sum of other effects is needed. This could include model comparison exercises aimed at evaluating the range of predictions and uncertainties for these relative contributions.

Comprehensiveness requires a long-term and spatially representative focus, and thus *a priori* planning of design of experiments, observations, and analysis (e.g. nested hierarchical design). Methods need to be developed for filling gaps in observations, in some cases by adding measurements, but in other cases by developing new techniques. Some of the separation of direct, indirect and past practices effects is currently not supported by known methodology. For example, assessing the contribution of past practices and indirect effects on growth in newly established afforestation and reforestation projects is difficult, although a large proportion must be due to growth of new trees.

Gaps in theoretical foundations in understanding and systems analysis need to be filled. There are a number of areas in which scientific understanding is weak, preventing attribution of carbon fluxes to indirect effects. For example, our current understanding of soil processes and nutrient cycling, fire cycles, frozen soils and atmospheric chemical feedbacks are not yet sufficiently comprehensive to generate robust predictions of carbon fluxes at regional to continental scales. The theoretical and research analytical framework must be strong enough to separate direct from the sum of indirect effects before "practicable" methodologies can be fully evaluated.

In order to complete the theoretical framework, particularly concerning indirect effects, carefully planned multi-factor experiments of responses of processes to factors such as air quality, CO_2, and nitrogen deposition are needed. These must be integrated with existing types of observation networks (inventories, remote sensing, and flux networks), and coordinated modeling activities on sensitivities of biological processes. Measurement methods need to be tested to ensure they can operate effectively in all regions and biome types (e.g. both tropics and subtropics).

It is critical to develop a uniform data policy to facilitate integration (e.g. air quality observations, multi-factor experiments). Without this integration, the separate observational, experimental and theoretical work cannot be combined to produce useable knowledge.

Integrated evaluation of carbon reservoirs and exchanges requires information on measurements of concentrations, emissions, economic activities (trade, transport, fate of harvested wood products) and ecosystem processes and controls. In addition, the measures of uncertainty in this overall framework must be useable and uncertainties from the contributing sectors must be correctly combined. Knowledge products must be delivered based on data and models undergoing continuing incremental improvements. The needed datasets include some that are that presently difficult to obtain (such as air-quality information). Historical information on past management, land-use practices, and disturbances at global scales must be available for the effects of past practices to be estimates and understood. A broad range of land and biome types require evaluation.

A research agenda for evaluating proposed schemes for factoring out effects (e.g. workshops to advance development) is needed, as currently we cannot point to studies that have attempted comprehensive factoring out. In particular, a potential coordinating role of the Global Carbon Project of the Earth System Science Partnership of the International Geosphere Biosphere Programme (IGBP) World Climate Research Programme (WCRP), and the International Human Dimensions Programme (IHDP) should be noted.

DEFINITIONS / GLOSSARY

Note: the WG I TSU will complete this glossary and append a list of acronyms used in the full report of the Expert Meeting.

ARD

Carbon Reservoir
A system (or component of a system) that has the capacity to accumulate or release carbon. Examples of carbon reservoirs are forest biomass, wood products, soils, and the atmosphere. Alternative terms used commonly are *carbon pool, compartment* or *carbon state variable*.

Carbon Stock
The absolute quantity of carbon held within a reservoir at a specified time.

Direct Human-Induced Activities:
Article 3.3 of the Kyoto Protocol covers defined activities of Afforestation, Reforestation and Deforestation. Article 3.4 covers activities under broad categories of Forest management, Cropland management, Grazing land management and Revegetation.

Forest Management Area
(to be taken from Kurz's presentation)

Heterotrophic Respiration
The production of CO_2 from the decomposition of organic matter by microbial and fungal organisms.

Indirect Human-Induced Effects:
Refer to the effects of human activities that are not classed as direct human-induced (see above). The Marrakech Accords explicitly consider CO_2 fertilization and Nitrogen deposition as indirect human-induced effects. In general a range of other effects can be significant, including pollutants and their toxic effects (e.g. ozone and acid rain), enhanced UVB radiation, the ration of direct to diffuse radiation, long-term climate change, invasive species, erosion, altered disturbance regimes (e.g. fire, storms, and insects).

Landscape

Natural Effects:
A number of natural effects play a very significant role in modifying carbon stock changes. Particular consideration should be given to short-term climate variability, natural effects on radiation (e.g. volcanic), baseline erosion rates, baseline disturbances (e.g. fires, storms, and insects).

NBP (Net Biome Productivity)
(extract from SRLUCF text)

NEP (Net Ecosystem Productivity)
(extract from SRLUCF text)

NPP (Net Primary Productivity)
(extract from SRLUCF text)

Past Practices
Refers to human activities occurring prior to a reference year (1990) and their consequent effects.

Plot

Stand