Carbon sink and CarbonSink+: from observations to global potential

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Summary

Carbon balance of forests is defined by three main processes; photosynthesis, autotrophic respiration, and heterotrophic respiration. Climate impact of forests include also non-carbon effects like albedo, biogenic aerosols, effect on clouds, evaporation and surface roughness.

A well-thought measurement setup as well as standardised procedures are essential for a meaningful and robust monitoring and the comparability of the observations at the same site and in inter-site comparisons. Depending on the mitigation project objectives and scale different combination of methodologies could be used including forest carbon inventories, chamber measurements, tower-based eddy covariance flux measurements, large-scale atmospheric greenhouse gas measurements, aircraft and satellite remote sensing.

In addition to GHGs, forests have other important climate effects. They change surface albedo (warming effect), are source of volatile organic compounds (VOC), have effect on aerosol particle formation and growth, increases amount of cloud condensation nuclei (CCN), and has effect on cloud formation as well as on the precipitation. Moreover, any modification of the carbon cycle by removing or increasing CO_2-binding vegetation has impact on the complex climate - carbon cycle feedback. We define these additional cooling effects as CarbonSink+. Accounting all these effects, this CarbonSink+ may increase the climate cooling impact of forests compared with pure carbon sink effect.

Land use based mitigation plays an important role in current Nationally Determined Contributions of Paris Agreement. Scientific findings indicate that through different actions land sector could provide up to 1/3 of the needed total mitigation through year 2030. However, permanence of ecosystem based carbon storages is still a challenge and trade-offs between different land use form exist and should be properly acknowledged in the mitigation projects.

We define in this report a cost effective, i.e. as simple as possible but good enough, measurement setup to verify both ordinary carbon sink and CarbonSink+ -effect. The methodology is planned for commercial applications, rather than for scientific purposes. The estimated prices of the instrumentation are based on present-day situation. In the conclusions of the report, we also describe first level principles and challenges which could help to formulate protocols for larger framework needed for the global commercial carbon market.

Extended summary

Paris Agreement emphasized the role of land-use sector in climate change mitigation. There is increased need for different scale of ecosystem based mitigation projects. The backbone of the conceptualized commercial measurement system and higher level steering regulation has to be connected to relevant scientific understanding. This ensures longer term sustainability and social acceptance of the emerging land-use based commercial carbon market. This means that individual methods are based on standardized measurement techniques for ensuring the verification of claimed carbon credits within system. Higher level commonly shared framework and transparent system protocols are also needed for the development of the regulation for commercial carbon mitigation projects.

In this report, we describe current state of scientific understanding related to ecosystem carbon sinks and storages, and other climate effects of forests. We also define in this report a cost effective, i.e. as simple as possible but good enough, measurement setup to verify both ordinary carbon sink and CarbonSink+ -effect. Chapter 1 describes different processes related ecosystem carbon sinks and storages. Chapter 2 describes state-of-art of different measurements. Chapter 3 describes other forest related climate effects than greenhouse gases (GHG), namely surface albedo (warming effect) and biogenic aerosols, and feedback loops between different effects which strengthen net climate cooling impact of forest cover, aka CarbonSink+. Chapter 4 describes scientific findings of the potential to mitigate climate change by strengthening terrestrial carbon sink by different land-use sector actions. On basis of other chapters, recommendation for the conceptualization of commercial carbon measurement system, main uncertainties and an estimate of related costs are given in Chapter 5.

Chapter 1: Forests cover 67 % of the global land area (FAO 2015). Forest vegetation removes carbon (C) from the atmosphere by taking up carbon dioxide (CO_2) via **photosynthesis.** Besides living biomass, C removed from the atmosphere is **sequestered** into dead plant parts and soil. Biomass and soil, thus, function as C **storages** in forests. Sequestered carbon is released by respiration. Plants need energy for several processes, for instance synthesis of new molecules and transportation of sugars. Plants utilize the energy bound in photosynthesis via **autotrophic respiration**. **Heterotrophic respiration** is the combination of microbial decomposition of dead plants parts and breaking up the organic compounds released to the soil as root exudates. Carbon flux is the movement of C through a unit area per unit time. If the **net C flux** of a surface, e.g. forest, is negative, the forest takes up more C than it releases C and acts as a C **sink.** In case the net flux is positive, forest is a **source** of C. Forest acts as a carbon sink when carbon storage increases, i.e. carbon is sequestration larger than released amount of carbon (e.g. respiration of trees, soil processes, wood harvesting). On a global scale, forests form a large sink of atmospheric C. Current terrestrial sink is 11,7 $GtCO_2$ $year^{-1}$ (3,2 GtC $year^{-1}$, http://www.globalcarbonproject.org/, Le Quere et al. 2018). Stopping **deforestation**, and increasing **afforestation** and **reforestation** can help to strengthen the ecosystem sinks of CO_2. An estimated 861 ± 66 Gt of C is stored in the world's forests (fossil and land-use change emissions together are 10.9 GtC $year^{-1}$). Forest biomes differ in their carbon structures as, for example, tropical forests have highest C storage in biomass, but boreal forests have largest C storage in soil. Forest management influences forest C storages. After tree harvest, the total carbon storage of a forest diminishes at least for a short term. Once new trees are established, the total C storage will gradually increase, but this takes from several decades up to hundred years in boreal conditions.

Chapter 2: The term forest carbon storage (or stock) describes the total amount of carbon stored in the soil and biomass of a forest. Carbon storage changes can be calculated either straightforward from the changes in carbon stocks or by integrating the net carbon fluxes over time. Observations need to consider the two major organic carbon pools, biomass and soil, and can be conducted in-situ and by remote sensing, and on multiple spatiotemporal scales, from plant organ to global level. The UN standards required for afforestation/ reforestation projects (e.g. within the programmes REDD+ and Clean Development Mechanism, CDM) might not be sufficiently profound and explicit to ensure emission reductions to be additional and not over-estimated. The usefulness of CDM methods depends also on the length of the commitment period, how interactions of different processes are covered, and if CarbonSink+ is of interest. Observations should be

started before land-use change such as afforestation/reforestation is conducted, in order to establish a meaningful baseline and to be able to verify the impact of the land-use change. Standardised protocols are available for most of the in-situ observation methods, such as the ones for measurements of terrestrial GHG fluxes and atmospheric GHG concentrations.

Forest carbon inventories need to consider the two major carbon pools in a forest ecosystem, biomass and soil carbon. Forest biomass includes above-ground living biomass (trees, understorey vegetation), below-ground living biomass (coarse and fine roots), as well as litter and deadwood as non-living biomass. Inventory could include sampling, allometric methods, terrestrial laser scanning, and all these could be coupled with process-based modelling. The result of a forest carbon inventory is expressed as changes in carbon stocks in tonnes of carbon per hectare or at a project level over a certain period of time.

The chamber technique for observing fluxes of different GHGs is particularly well-suited for laboratory-based and in-situ process-level studies. Observations with the chamber technique might be an option for carbon stock change observations during the first years after afforestation, when the seedlings still fit into the chambers, or for observations of the gas exchange of forest understory and soil. A chamber generally encloses the compartment of interest such as a leaf or branch or a certain tree stem or soil surface area. It is equipped to measure the gas (particularly CO_2, but also CH_4 and N_2O) concentration change within the chamber, based on which the gas exchange between the compartment of interest and the atmosphere is calculated.

The eddy covariance technique is a widely used and one of the most direct and accurate methods for quantifying exchanges of CO_2, CH_4, N_2O, H_2O, various other gases and aerosols as well as energy between the surface of the earth and the atmosphere at ecosystem scale. Eddy covariance measures the gas exchange on ecosystem-scale and requires a minimum area of homogeneous land cover in dependence on the size of its footprint (source area of the flux). The minimum fetch of Eddy measurement could vary from 100 m in case of short vegetation (e.g. 1 meter tall grasses in wetland) to 1 km in case of mature forest stand (trees of tens of meters height) from wind direction. Minimum area could be calculated using fetch as a radius of circle. Cautious and standardised post-processing of the raw flux measurements is essential for the reliability and intercomparability of the observations and should include footprint modelling to estimate the source/sink area of the measured fluxes

For large scale observations, platforms for continuous monitoring and flask sampling are, for instance, continental stations (tall towers specifically built for this purpose or existing television, radio and cell phone towers, mountain and coastal stations and airborne platforms (aircrafts, helicopters). The source area of an atmospheric measurement is increasing with the height at which the air is sampled and can be on the order of 100-1000 km. For the estimation of source distributions on regional scale, observations from a distributed network of stations and regional land cover maps are required.

Aircraft and satellite remote sensing (like Landsat, MODIS) can support several ways the quantification of forest carbon storage and its changes on different spatial scales and new techniques are progressively developed (Unmanned Aerial Vehicles [= drones] have spatial scale of few hectares, aircraft from 1 km^2 to hundreds of square kilometres, and satellites > tens of square kilometres) while combining datasets retrieved in different spatial and temporal scales by different satellites helps to refine the resolution of the remote sensing products.

Chapter 3: Albedo can range from 0 (black surface that absorbs all radiation) to 1 (perfect mirror that reflects all radiation). Land covered by green vegetation typically has albedo of 0.05–0.28. Afforested sites are often originally open pasture or grassland, thus afforestation decreases albedo, i.e. have warming effect. The change in the annual shortwave radiation balance can be significant and comparable to the radiative forcing caused by changes in carbon storage.

The VOCs produced by forests (BVOC) will form new aerosol particles and secondary organic aerosols (SOA) which generates more CCNs, which increases cloudiness and thicker clouds increasing cloud albedo. Increased cloud albedo can have major cooling effect and counterbalance the warming effect of forests' low surface albedo. However, this process depends on the specific emitted VOCs. In the boreal region, VOCs – especially monoterpenes – can have major cooling contribution to the radiative forcing and therefore also to the regional climate, while the effect of isoprene which is main VOC in tropics is not that effective. A negative climate feedback mechanism known as CO_2 fertilization may cause an increase in the gross primary production (GPP) of an ecosystem due to higher atmospheric CO_2-levels. Enhanced photosynthesis increases BVOC emissions. Also temperature increase boosts emissions of many BVOCs. This feedback loop affects finally to CCNs , cloud albedo , the diffuse to global radiation ratio and may strengthen cooling effect of forests further. We define these additional cooling effects as CarbonSink+.

Chapter 4: The importance of land-use sector for reaching targets of restricting global warming <2°C is emphasized by Paris Agreement. Summed up, land-use based mitigation forms 25% of total mitigation in current Nationally Determined Contributions (NDC). These approaches include large uncertainties and therefore mitigation by land use sector needs to be done on a sound scientific basis. Natural Climate Solutions (NCS) present 20 different actions for three major land biome (forests, agricultural and grasslands, and wetlands) for strengthening carbon sinks in these ecosystems. The NCS could provide even up to 1/3 of the needed total mitigation through year 2030 when cost-efficiency is accounted for (mitigation cost <100 USD $tnCO_2eq^{-1}$ year-1). However, taking into account the CarbonSink+ this effect could be even bigger.

The persistence of the carbon stored in the ecosystems in the mitigation projects is well-known challenge. How to suppress abiotic (e.g. storms) and biotic damages (insects, pathogens etc.) in large regions needs specific attention in the ecosystem based mitigation projects. Also aspect to keep in mind is that reducing rates of deforestation constrains the land available for agriculture and grazing, with tradeoffs between diets, higher yields and food prices. Also the importance of old forests increases along the efforts to increase the long-term storage of carbon in ecosystems. The carbon dynamics in the old forests are not well known although common belief of old forests being carbon sources is not valid in the light of current scientific understanding. Focused measurements both in pristine Northern boreal forests and in tropical forests are in demand if long-term success of these mitigation projects are wanted to ensure. The only sustainable way in the long-term to obtain mitigation through NCS and land use intensification is to implement them in locally appropriate ways with best practices that maximize resilience.

Chapter 5: Conceptualised measurement scheme has to be flexible enough for being applicable in various situations. We divided the scheme to **planning phase** (steps 1-3) and **operational phase** (steps 4-6) whose include altogether six (6) steps. **Step 1:** Ecosystem description. Each mitigation project has to consider the specifics of vegetation zone like climate, biome, size of target area, and management history. The project for strengthening ecosystem carbon sinks should take place only in the locations fulfilling the criteria. **Step 2:** Initial vegetation and carbon inventory. This phase includes different inventory methods for vegetation and soil, e.g. traditional forest mensuration for aboveground vegetation and systematic acquisition of soil samples in the resolution covering both horizontal and vertical variation. **Step 3:** Management and Monitoring plans. This step includes description of the actions which will take place for fulfilling the objectives of the mitigation project, and number of afforested areas, their sizes, and the desired frequency of the observations for creating a coherent monitoring / observations strategy. **Step 4:** Actual monitoring / observations (see chapter 5). **Step 5:** Post processing of measurements and data analysis. **Step 6:** Repetition of cycle.

Contents

1. Current understanding of carbon sink state and dynamics – Global, Europe, Finland

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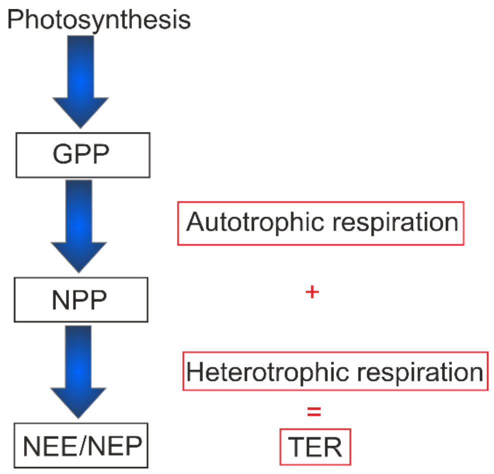
1.1 Carbon sequestration in forest ecosystems

Forests cover 67 % of the global land area (FAO 2015). Forest vegetation removes carbon (C) from the atmosphere by taking up carbon dioxide (CO_2) via **photosynthesis.** The products of photosynthesis are different forms of sugars, which the plants store in their tissues. Plant **respiration**, or **autotrophic respiration**, takes place when plants break up the sugars formed in photosynthesis to use the energy bound in them. It is an inverse reaction of photosynthesis, and releases CO_2 to the atmosphere (Hari et al. 2013a). Besides living biomass, C removed from the atmosphere is **sequestered** into dead plant parts and soil. Biomass and soil, thus, function as C **storages** in forests**.** Soil C sequestration depends on the amount of input from litter-fall and fine roots, atmospheric input of organic matter, lateral transport of dissolved inorganic and organic C in water runoff, and **soil respiration.** Soil respiration includes autotrophic respiration of living roots and **heterotrophic respiration** from microbial decomposition of dead plants parts and breaking up the organic compounds released to the soil as root exudates (Ardö 2015, Pumpanen 2013).

Carbon dioxide is essential for life, but it is also **a greenhouse gas (GHG),** meaning that it absorbs and emits thermal radiation. Additionally, there are other important GHGs, such as methane (CH_4) and nitrous oxide (N_2O). Referring to their climate impact, quantities of GHGs are expressed as CO_2-equivalents. This common unit, allowing for direct comparisons, represents the amount of CO_2, which would have the equivalent global warming impact. It is calculated as a product of the quantity of the GHG and its global warming potential (GWP, also called cumulative forcing, dependent on lifetime of the GHG in the atmosphere). According to the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) the GWP values of CO_2, CH_4 and N_2O for a 100-year time horizon are 1, 28 and 265, respectively, whereby for CH_4 and N_2O climate-carbon feedbacks are not included (IPCC, 2014).

Essential concepts and definitions related to carbon cycling are described in Fig. 1.1. The forest C cycle is visualized in Fig. 1.2. It shows, along with the C storages, **fluxes** of C between the atmosphere and ecosystem. Carbon flux is the movement of C through a unit area per unit time. Usually the unit area is a square meter in the ground, perpendicularly to the flux of air. Unit time is seconds. If the **net C flux** of a surface, e.g. forest, is negative, the forest takes up more C than it releases C and acts as a C **sink.** In case the net flux is positive, forest is a **source** of C (Burba and Anderson 2010). Forest acts as a carbon sink when carbon storage increases, i.e. carbon sequestration is larger than the released amount of carbon (e.g. respiration of trees, soil processes, wood harvesting).

On a global scale, forests form a large sink of atmospheric C. The input of different forest biomes on the **global forest C sink** is in Table 1.1, along with information about the total C storages of the biomes. The latest calculation of the global land CO_2 sink, as an average from 2007-2018, is 3.2 Pg C year^{-1} (Le Quére et al. 2018). The C fluxes and storages related to forest ecosystems are in Fig. 1.2. **Deforestation**, mentioned in the figure under land use change, means cutting down a forest and using the area for non-forest use. It is a large global source of CO_2 to the atmosphere. **Afforestation** and **reforestation** can help to increase the sinks of CO_2 (Ciais et al. 2013). Afforestation means establishing new forests to regions without previous forest cover in the recent history, and reforestation is restocking of deforested or depleted areas with trees (Global Forest Atlas 2018).



GPP (Gross Primary Production) = the total amount of carbon taken up by plants in photosynthesis

Autotrophic respiration = Respiration of the primary producers (plants) in the ecosystem

NPP (Net Primary Production) = Net production of organic matter by plants in an ecosystem scale

Heterotrophic respiration = carbon lost by organisms other than the plants, aka decomposition of dead organic matter

TER (Total Ecosystem Respiration) = autotrophic + heterotrophic respiration

NEE / NEP (Net Ecosystem Exchange / Production) = the amount of carbon accumulated in the ecosystem

Figure 1.1 Concepts and definitions related to describing C exchange between atmosphere and ecosystem. Modified from Kirschbaum et al. 2001. E.g. NPP = GPP – Autotrophic respiration, NEE/NEP = GPP- TER, NEE/NEP = NPP – Heterotrophic respiration, and GPP = NEE/NEP + TER. The GPP could be estimated e.g. $GPP = \beta f_{\mathrm{aPPFD}} \sum_{d} \Phi_{d} \prod_{i} f_{id}$,where f_{aPPFD} is the fraction of photosynthetic photon flux absorbed by the canopy), β is the potential light use efficiency (gC mol^{-1}), Φ_d is photosynthetic photon flux density of day d (PPFD, mol m^{-2} day^{-1}), and f_{id} are values on day d of environmental modifiers related to variable i ($i = L, S, D, W$ representing light, temperature, vapour pressure deficit and soil water, respectively). The NPP varies between vegetation zones and ecosystems but mean value is conservative being close to 0.5 x GPP.

In many regions, especially in the semi-arid areas in the tropical zone, afforestation is considered as an important carbon sequestration method for climate change mitigation (Ardö 2015). Deforestation takes place especially in the tropical regions. It makes the tropical forests nearly carbon-neutral although they cover the largest forest area compared to other forest biomes, and comprise about 70 % of the gross C sink in the world's forest (Pan et al. 2011). Thus, the net global forest sink occurs via boreal and temperate forests (Pan et al. 2011).Land-use, land-use change and forestry, including afforestation, form one pathway towards halting climate warming through the reduction of atmospheric GHG concentrations, or at least the reduction of emissions to the atmosphere. However, carbon sequestration alone does not tell the full story. Vegetation-climate feedback loops (e.g. Luyssaert et al., 2018) need to be considered when evaluating the climate impact of ecosystems and management practises (chapter 3).

Tree and plant species of different forest biomes are adapted to varying kinds of growing environments. In tropical land ecosystems, both dry and moist, the CO_2 flux can vary because of El Niño-Southern Oscillation (ENSO). ENSO has positive and negative phases; the positive phase, which usually means a higher land CO_2 source, is called El Niño. The negative phase with higher land CO_2 sink is La Niña. ENSO also has a neutral phase (Ciais et al. 2013, Tagesson et al. 2016). Most forest biomes experience seasonality in either rain or growing season length (Pan et al. 2013) For instance, in a West African grazed semi-arid savanna ecosystem, the CO_2 flux levels can be very high at the peak of a rainy season. About 30 days after the onset of a rainy season, once the vegetation is active and established, the ecosystem turns into a C sink. After the rainy season the CO_2 flux rate as well as soil moisture decrease strongly (Tagesson et al. 2016).

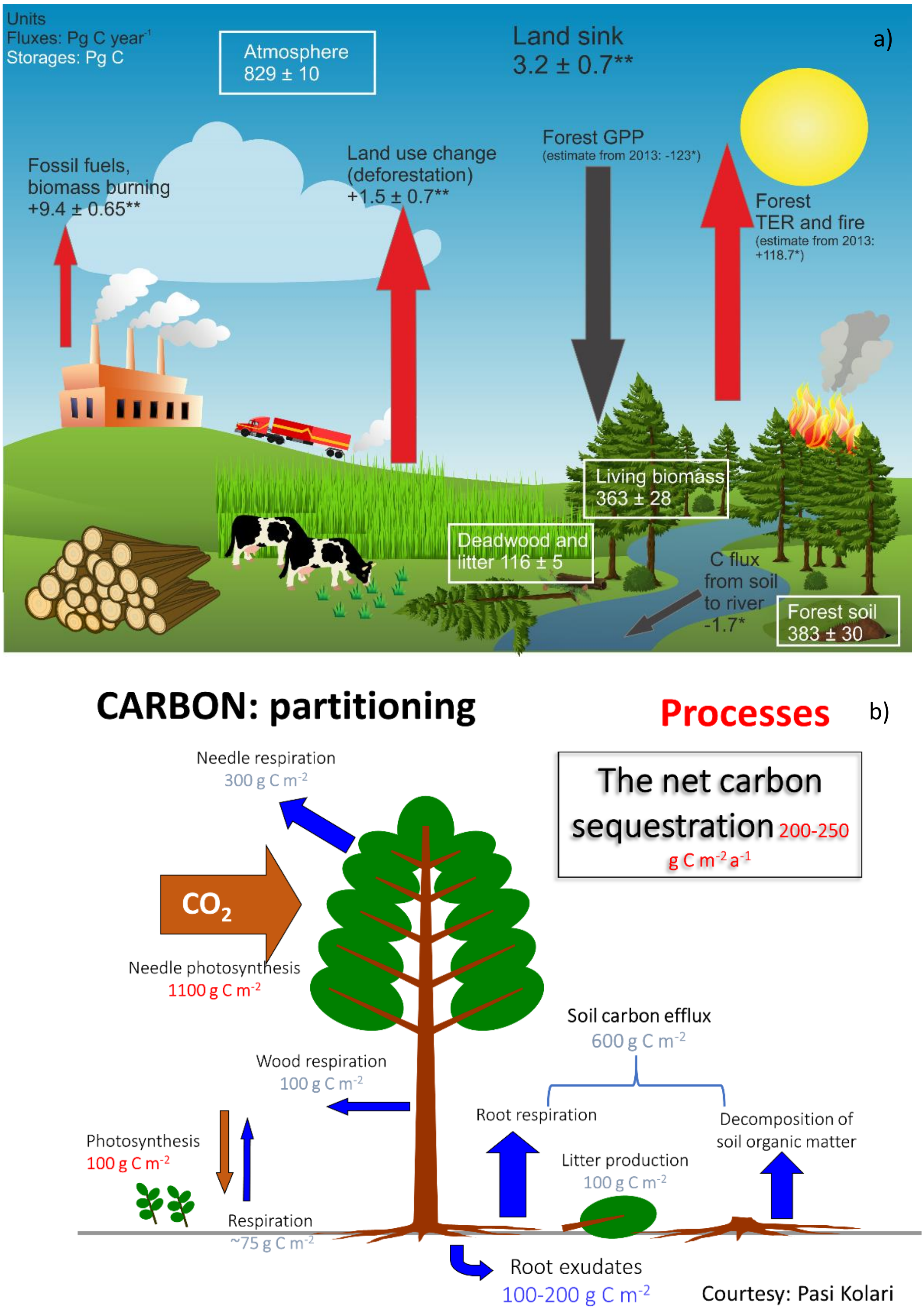


Figure 1.2 a) Fluxes and storages of atmospheric carbon related to forest ecosystems. Red arrows denote release of carbon from ecosystem to the atmosphere (marked with plus sign). Black arrows mark the uptake of carbon from atmosphere to ecosystem (marked with minus sign). White boxes denote carbon storages. Storages are based on Pan et al. 2011, those marked with * are from Ciais et al. 2013. The values marked with ** are from the latest Global Carbon Budget (Le Quére et al. 2018) , so that the value for fossil fuels is based on Boden et al. 2017, land use change bases on Hansis et al. 2015, Houghton and Nassikas 2017, and Le Quére et al. 2018, and land CO2 sink bases on Le Quére et al. 2018. The land sink is based on GPP, TER and land use change. b) Numbers based on observations at Hyytiälä.

Soil texture and nutrient availability affect forest's capacity to bind CO_2. In boreal forests nitrogen (N) is the growth limiting nutrient, but a co-limitation of N and phosphorus (P) is globally very common, and in tropical and temperate forests single P limitation also occurs (Augusto et al. 2017). For instance, in eastern Amazonian forests, the soil is weathered and strongly limited with P. This is why the NPP rates of the eastern Amazonian forests are lower than NPP rates of the western Amazonian forests, where the soil is younger, less weathered and richer in nutrients. Soil parent material is crucial in P limitation, while climatic factors affect N limitation the most (Augusto et al. 2017).

Understory vegetation also plays a role in forest carbon dynamics. If the tree canopy is scarce, and light hits the forest floor freely, understory vegetation can form an important part of the CO_2 flux between forest and atmosphere (Hari et al. 2013b). In boreal forests ecosystems, the GPP by understory vegetation has been measured to represent as much as 60 % of the forest GPP (Ikawa et al. 2015).

1.2 Respiration in forest ecosystems

Plants utilize the energy bound in photosynthesis via respiration. Plants need energy for several processes, for instance synthesis of new molecules and transportation of sugars. Although growth and maintenance respiration can be differentiated as terms, it is very hard to separate them in practice, as their processes are similar and they take place concurrently (Bäck et al. 2008). Maintenance respiration is accounted as proportional to plant size (Amthor 2000) and strongly correlated with leaf tissue N concentration. Nitrogen is an essential ingredient of proteins (Ryan 1991). Growth respiration is considered to be proportional to GPP (Amthor 2000). Respiration and photosynthesis occur simultaneously during the daytime, but during the nighttime plants only respire (Bäck et al. 2008). Temperature changes affect respiration more than they affect photosynthesis (Ryan 1991). Additionally, respiration has other drivers and regulators, whose importance depends on the climate and location of the forest. Respiratory enzymes limit respiration the most in cold conditions, while substrate and adenylate concentrations regulate respiration rates in warm environments (Atkin and Tjoelker 2003). As the same environmental drivers cause different effects in respiration and photosynthesis, climate change may modify their balance. This, in turn, could change NPP (DeLucia et al. 2007)

Trees respire from many parts, as likewise with leaves, also roots and stem respire. In addition to autotrophic respiration, heterotrophic respiration is an important part of C cycle in forest ecosystems. Soil respiration, including also root respiration, creates an outward flux of CO_2 from soil to the atmosphere. This **efflux** is an important part of the forest carbon cycle. Soil respiration is dependent on temperature, which affects the functioning of, for example, decomposing microbes (Pumpanen 2013). Forest soils are typically net sinks of C, as litter fall is bigger than soil respiration (Ågren et al. 2008).

1.3 Carbon storages and carbon storage changes

An estimated 861 ± 66 Pg of C is stored in the world's forests (Fig. 1.2a). The storage of soil C may be underestimated, as the standard 1-m soil depth, used in the estimations, excludes some deep organic soils in boreal and tropical peat forests. Forest biomes differ in their carbon structures as, for example, tropical forests have highest C storage in biomass, but boreal forests have largest C storage in soil (Pan et al. 2011). **Mangrove forests have one of the biggest carbon storages of all ecosystems** (Simard et al. 2019). The division of the C stock to different forest biomes is in Table 1.1.

Forest management influences forest C storages. After tree harvest, the total carbon storage of a forest diminishes at least for a short term. Especially with clear cuts, this decrease is immediate and evident and leads to increased CO_2 emissions due to accelerated decomposition of accumulated organic matter and harvest residues. Once new trees are established, the total C storage will gradually increase, but this takes from several decades up to hundred years in boreal conditions (McKinley et al., 2011). Recent modeling studies imply that in the long-term, climate change induced risk for natural disturbance is an important factor affecting forest total C storage. Such disturbances can be insect outbreaks, fire or drought, which can destroy large forest stands and turn them from sinks to sources of atmospheric CO_2 (Bradford et al. 2013, Kalies et al. 2016). The responses of soil C to forest management are small on an annual basis, but monitoring for longer time periods have revealed diminished soil C storages due to forest management (Johnson and Curtis 2001, Kaarakka et al. 2016).

Afforestation practices have become more common within the last decades. The afforested areas are still relatively small trial areas compared to what would be needed to compensate current global C emissions. For climate change mitigation purposes afforestation works most efficiently in the tropics (Claussen et al. 2001, Yosef et al. 2018). A promising possibility for afforestation lies in semi-arid regions (Ardö 2015, Yosef et al. 2018, Liu et al. 2018). The best areas seem to be those under monsoon effect (Yosef et al. 2018), which get some rainfall, but their climate is not too humid. Afforestation can affect local meteorological conditions, reaching to areas outside the afforested area. Fifteen-year simulations of effects of afforestation over large areas of the semi-arid regions of Sahel and North Australia (both with annual 300 mm precipitation) demonstrated increasing precipitation rates and lower surface air temperatures. The simulation period included three significant El Niño and four significant La Niña years (Yosef et al. 2018). The same was noticed in a smaller area of Yatir forest, where its cooling effect was still clear 5 km away from the forest, where the day was 0.5-1 °C cooler than further away from the forest (Yosef et al. 2017). Yatir forest is 35-year-old afforestation system in Israel, on the lower slopes of Hebron hills at the edge of a desert (Grünzweig et al. 2003). Afforestation enhances soil moisture conditions. This may indirectly enhance C sequestration, as plants, which cannot tolerate drought well, will be able to move to new areas.

In addition to the increase in aboveground C storage, afforestation increases soil organic carbon stocks. Root growth and biomass accumulation underground is an important factor for this. In Yatir forest, the total ecosystem organic C stock was approximately 2.5 times the C stock of a nearby shrubland (Grünzweig et al. 2007). Generally, soil carbon accumulation is larger in afforestation of tropical region, compared to temperate and boreal region. Also, broadleaved trees seem to increase soil C stock more than conifers, possibly because higher litterfall with broadleaved trees dropping leaves for winter/dry season (Liu et al. 2018). Since tree biomass as a C storage varies due to, for example, forest management or natural death, should more C be stored in soil to enable greater continuity of storage. In a hot, semi-arid, shrubland afforestation of shrubland proved to be successful in especially soil C sequestration. Possible reasons for the promising results were increased N use efficiency, new live and dead root biomass, and reduced litter decay rates caused by lowered litter quality, as conifers were grown instead of previous, broadleaved shrub cover. In addition to added soil C from the established forest, about 50 % of the previous shrubland soil C remained in the afforested area (Grünzweig et al. 2007).

Carbon storages in the tropics and boreal forests are large. Both regions face an increasing fire risk caused by climate change induced droughts. In the tropics, deforestation also still poses a risk to the C storage. Although its rate has decreased in some regions, such as in Brazil, it has increased in other regions, such as in Malaysia and Indonesia (Pan et al. 2011, Hansen et al. 2013, Rappaport et al. 2018). Temperate and boreal forests seem to continue as C sinks even though their risk of suffering from natural disturbances increases due to climate change (Kalies et al. 2016).

Table 1.1. Forest biomes of the world and their contribution to C sequestration between (Pan et al. 2011, Pan et al. 2013). Sink rates and storage values are based on data from time period of 1990-2007, and thus, may have changed since then. The overall division to different biomes should have stayed more or less the same.

Forest biome	**Mean annual temperature (°C)**	**Total annual precipitation (mm)**	**Area (Mha)**	**Total carbon density in biomass (Mg C ha^{-1})**	**Carbon sequestration rate/sink**	**Total carbon storage**
Tropical rainforest	~ 20 - 25	>1500	1458	145 ± 53		
Tropical moist deciduous forest	> 15	1000 - 2000	1105	73 ± 47	Sink of the whole tropical forest biome (inlc. regrowth forests):	Stock of the whole tropical forest biome :
Tropical dry forest	> 15	500 - 1500	747	53 ± 35	2.7 Pg C year^{-1}	471 Pg
Tropical shrubland	> 15	200 - 500	831	71 ± 45	sink of tropical intact forest: 1.18 Pg C year^{-1}	
Tropical mountain systems	< 18	700 - 2000	453	124 ± 54		
Subtropical humid forest*	> 14	600 - 1000 +	468	66 ± 46		
Subtropical dry forest	> 7	300 - 1000	159	67 ± 60	-	-
Subtropical mountain systems	< 12	500 - 2000	486	77 ± 41		
Temperate oceanic forest	5 - 11	600 - 3500	181	208 ± 131		
Temperate continental forest	~ 10	750 - 1500	695	61 ± 31	Sink of the whole temperate	Stock of the whole temperate
Temperate mountain systems	< 10	1000 - 2500	723	59 ± 22	0.8 Pg C year^{-1}	118.6 Pg
Boreal coniferous forest	-12 - 6	< 500	865	48 ± 24		
Boreal tundra woodland	-15 - 0	150 - 250	395	7 ± 6	Sink of the	Stock of the whole boreal

Boreal mountain system	-14 - 5	400 +	630	19 ± 14	whole boreal forest biome: 0.5 Pg C year^{-1}	forest biome: 271.5 Pg

* There are no C sink or storage values for subtropical biomes. It's in included the tropical forest biome.

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2. Carbon storage measurements and their reliability

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2.1 Observing forest carbon storage and its changes on different spatiotemporal scales

Forest carbon storage and its changes can be observed using versatile methods. The term forest carbon storage (or stocks) describes the total amount of carbon stored in the soil and biomass of a forest (see section 1.1). Carbon storage changes can be calculated either straightforward from the changes in carbon stocks or by integrating the net carbon fluxes over time. Carbon fluxes comprise the net exchange of carbon with the atmosphere and the lateral transport of carbon, for instance as dissolved organic carbon (DOC) in the groundwater and inland waters, or in the course of management practices such as fertilisation and harvest. Observations need to consider the two major organic carbon pools, biomass and soil, and can be conducted in-situ and by remote sensing, and on multiple spatiotemporal scales, from plant organ to global level (Fig. 2.1) and from split-second to decadal scale. Whereas small-scale studies, particularly on plant organ and even on molecular level, focus on a thorough understanding of the underlying mechanisms of carbon sequestration, observations from plot level up to global level aim to quantify and explain the spatiotemporal patterns and dynamics of forest carbon sinks and sources. The integration of various methods is most beneficial to get the full picture and to understand the dynamics of carbon cycling on the different scales. Forest carbon storage and the synergy of distinct observation techniques are intensively studied, for instance, at the Finnish forestry field station in Hyytiälä as part of SMEAR (Station for Measuring Ecosystem-Atmosphere Relations) Network (SMEAR II, section 2.5).

For monitoring purposes as within a carbon compensation market, carbon storage change observations should cover full years due to the seasonal variation in the carbon dynamics of a forest, and observations should be planned for the long-term, as the carbon storage capacity changes during the lifetime of a tree (Curtis et al., 2018). A well-thought measurement setup as well as standardised procedures are essential for meaningful and robust observations and the comparability of the observations at the same site and in inter-site comparisons. The selection of the methods depends on the specific goals and needs of each project and should be appropriate to answer the question. Whereas an intense, research-dedicated setup such as at SMEAR II is often too demanding for the regular monitoring of forest carbon storage changes and the verification of the effectiveness of afforestation, the UN standards required for afforestation/ reforestation projects (e.g. within the programmes REDD+ and Clean Development Mechanism, CDM) might not be sufficiently profound and explicit. The study of Cames et al. (2016) reports that the CDM still has fundamental flaws in terms of overall environmental integrity. Their results suggested that most of the projects (85%) had a risk to over-estimate emission reductions and even more importantly the realized emission reductions were not additional. Only in very small proportion of the projects (2%) (and only 7% of potential Certified Emissions Reduction, CER, supply) emission reductions were found additional and not over-estimated. The usefulness of CDM methods also depends on the length of the commitment period, how interactions of different processes are covered, and if CarbonSink+ is of interest.

Observational data should be openly available and accompanied by thorough metadata records in order to be useful. Transparency is of utmost importance in order to create trust and reliability. Apart from their utilisation for the carbon compensation market, forest carbon storage observations at afforested sites are of interest, e.g., for the climate change scientific/ modelling community (see section 2.4.1).

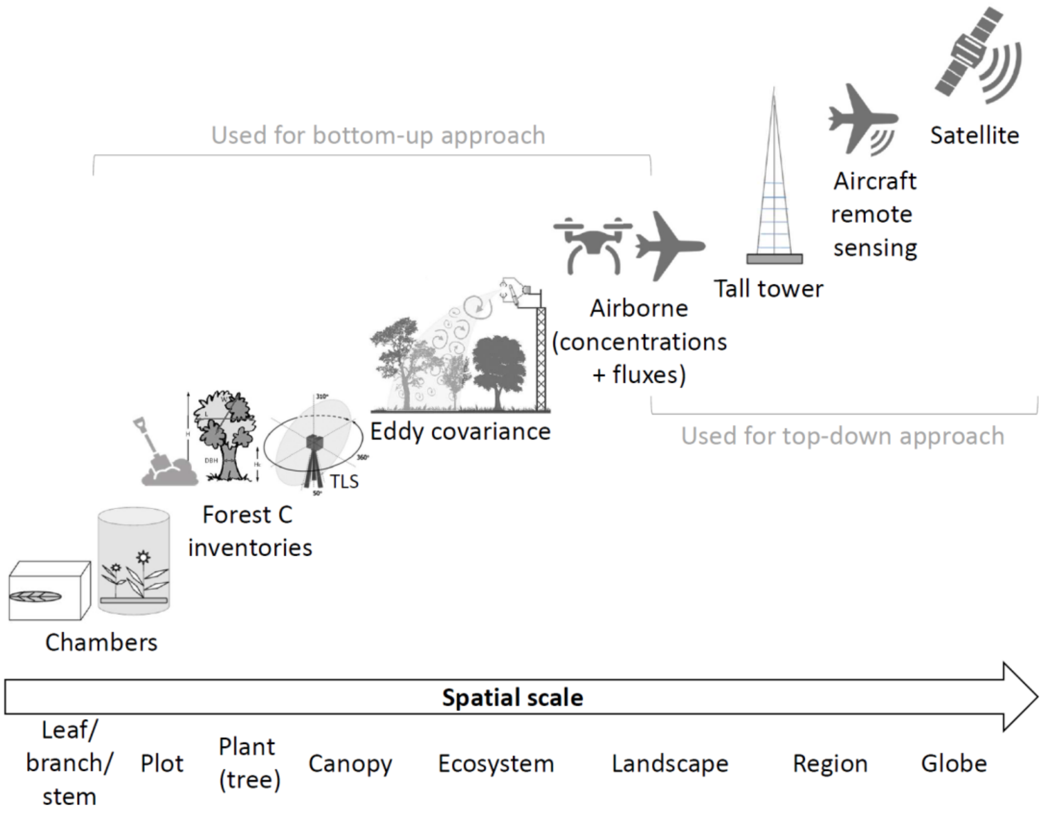

Figure 2.1 Observations of carbon storage and its changes in forest ecosystems on different spatial scales (C = carbon, TLS = Terrestrial laser scanning). Observations at plot- to global level serve as data basis for bottom-up and top-down approaches to estimate regional and global carbon and GHG fluxes (for sources of pictures see reference section).

Each observational method has inherent sources of error, which have to be considered during the selection of the methods and appropriately handled in the quality control and data analysis. The uncertainties have to be provided when publishing or sharing the data as they are required for a proper evaluation of the observations. Uncertainties of observations can be described as sampling/ representativeness uncertainties (related to spatial distribution or fetch of measurements) and measurement uncertainties (related to the measurements themselves), both of which can be random or systematic. Random uncertainties are caused by unknown and unpredictable changes, which may occur in the environmental conditions or in the measuring instruments (e.g. noise). Systematic uncertainties can be caused by an inappropriate calibration or measurement setup or within the post-processing of measurement data. Systematic measurement uncertainties accumulate during the spatial or temporal upscaling of observations, whereas random errors are typically levelled off. However, a systematic measurement uncertainty at one site or a specific time may turn into a random measurement error during upscaling of observations at several sites or several observations in time. The total uncertainty of data is a complex blend of measurement and sampling/ representativeness uncertainties.

Protocols for standardised measurements are available for most of the in-situ observation methods, such as the ones for measurements of terrestrial GHG fluxes and atmospheric GHG concentrations, which were developed within the pan-European research infrastructure ICOS (Integrated Carbon Observations System, Franz et al., 2018). ICOS facilitates long-term, geographically distributed and standardised carbon and GHG (CO_2, CH_4, N_2O, H_2O) observations within the atmosphere, terrestrial ecosystems and oceans in order to monitor climate change. In the case of terrestrial GHG flux measurements, protocols are provided for eddy covariance, chamber measurements and a large set of complementary data including lateral carbon transport, vegetation and soil characteristics, supporting the interpretation, upscaling and modelling of observed ecosystem carbon and GHG dynamics (published in International Agrophysics, Issue 32(4), 2018; specific instruction documents providing guidance to their practical implementation in the field are available at www.icos-etc.eu/documents/instructions).

2.2 Method description and standards

In this section the different observation methods are explained and respective standards are mentioned, starting with inventories of forest carbon stocks and the quantification of their changes over time. Subsequently, the methodology to quantify the net exchange of carbon with the atmosphere is focussed, followed by atmospheric GHG concentration measurements, which allow for carbon source and sink detection on larger scales. Finally, the possible applications of remote sensing are thematised. The Pros and Cons of each method is given in Table 2.1.

2.2.1 Forest carbon inventories

Forest inventories are traditionally conducted to determine the economic value of forest resources. Along with the increasing awareness of climate change and the need of mitigation measures, particularly the related carbon stocks are of interest. Forest carbon inventories need to consider the two major carbon pools in a forest ecosystem, soil (containing soil organic carbon) and biomass, whereby the latter includes above-ground living biomass (trees, understorey vegetation), below-ground living biomass (coarse and fine roots) as well as litter and deadwood as non-living biomass. Ravindranath and Ostwald (2008) published a handbook covering all aspects of the forest carbon inventory process including the monitoring of carbon stock changes with step-by-step descriptions of methods. The result of a forest carbon inventory is expressed as changes in carbon stocks in tonnes of carbon per hectare or at a project level over a certain period of time. Of the two main methods of estimating forest carbon stock changes, i.e. ‘Gain-Loss’ and ‘Stock-Change’ (IPCC, 2006), the second is more accurate and appropriate for afforestation projects, determining the change in carbon stocks for each pool from the difference in carbon stocks measured at different time points (Ravindranath and Ostwald, 2008).

Table 2.1 The spatial and temporal scale, and Pros & Cons of different measurement methods.

Method	Temporal scale	*Spatial scale	Pros	Cons
Chambers	hourly	Leaf...tree / plot	+ detailed information on ecosystem processes + relatively simple and inexpensive	- upscaling for larger areas inaccurate - measurement of long-term trends uncertain - year-round operation challenging in snowy climate - maintenance need
Manual forest and soil inventories	annual… multi annual	Tree…stand	+ simple and proven method, does not require expensive hardware or high technical expertise + can be applied to area of any size and topography + the only method for getting explicit information on soil carbon stock	- laborious for large areas - allometric equations not available for all tree species and ecosystem types, additional destructive sampling may be needed - uncertainty of belowground biomass and soil carbon stock - very low time resolution
Terrestrial or Airborne Laser Scanning	monthly…annual	Tree…stand	+ accurate and easy proxy for tree growth + less laborious than manual inventory, particularly for large areas + spatial variability can be assessed precisely	- not commercially available yet - expensive hardware and requirement of technical expertise - neglect soil processes
Eddy Covariance (EC)	hourly	Stand	+ proven and standardized method + integrates soil and plant processes, also respiration + area of several ha can be covered by measurements at one location + consistent in the long term + continuous with high level of automation	- investment costs and requirement for technical expertise - requires flat terrain and relatively homogeneous source area
Airborne fluxes	daily	Stand/landscape/ regional	+ possible to cover large areas	- high costs and requirement for technical expertise - campaign wise method
Tall towers	daily	Regional	+ consistent estimates of regional GHG balance in the long term	- high investment cost to hardware and requirement of technical expertise - the source area is very large, estimating the GHG balance of single small area practically impossible
Remote sensing (aircraft & satellite)	monthly…annual	Landscape/regional/ continental/global	+ consistent data on surface and atmospheric properties over large areas and extended periods of time	- coarse spatial and temporal resolution - requires local ground truth for reference - neglect soil processes

*Plot defined here in the meaning of sampling area within study site. Plot size can vary from 1 m^2 up to a few hectares. Stand has a common definition as an aggregation of trees occupying a specific area and sufficiently uniform in species composition, size, age, arrangement, and condition as to be distinguished from the forest on adjoining areas. Stand size can vary from under one hectare to several hectares. Landscape defined here as a spatially heterogeneous area containing several interacting stands, scale from a few kilometres to 10s of kilometres. Regional scale is from 10s kilometres to 1000s of kilometres.

Within ICOS, precise estimates of changes in soil organic carbon stocks along with quantifications of changes in biomass carbon and lateral carbon transport (protocols: Saunders et al., 2018, Arrouays et al., 2018, Gielen et al., 2018) are used to provide an independent assessment of long-term net ecosystem carbon exchange besides continuous eddy covariance measurements. The spatial sampling design is thereby adjusted to the eddy covariance footprint.

Forest carbon inventories are required for national GHG inventories and used for measurement, reporting, and verification (MRV) purposes within climate change mitigation projects and programmes initiated by the UNFCCC as important pillars of the Kyoto Protocol, such as the Clean Development Mechanism (CDM, https://cdm.unfccc.int/about/index.html), which includes afforestation and deforestation activities, and the UN-REDD programme (United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries, http://www.un-redd.org/). The goal of CDM is to increase the carbon stocks in the project area in addition to the stock changes that would have occurred without the project (baseline scenario; Ravindranath and Ostwald, 2008). CDM Gold Standard (https://www.goldstandard.org) is the strictest standard for climate change mitigation projects further making measurable contributions to sustainable development, which can also be used for emission reductions projects in the voluntary carbon market. Both UN-REDD and CDM provide guidelines for cost-effective project-level forest carbon inventories:

- Standard operating procedures (SOPs) provided for CDM projects (https://unfccc.int/resource/docs/publications/cdm_afforestation_field-manual_web.pdf). Project participants are actually required to follow the country-specific practices for forest inventories. However, they can alternatively follow the SOPs in case they do not have access to those practices.
- Monitoring guidelines provided by UN-REDD for nationally led REDD+ processes (http://redd.ffpri.affrc.go.jp/pub_db/publications/cookbook/index_en.html), representing a flexible system to account for differing circumstances of each participating country.

The flexible monitoring systems aim to increase the access of developing countries to the UN-REDD programme and CDM project.

Some general remarks on the methodology for the estimation of the distinct forest carbon pools are given in the following subchapters.

2.2.1.1 Biomass

The carbon stored in forest biomass is estimated on the basis of biomass inventories, which are conducted every x years depending on the expected changes in biomass. A generalised estimate of carbon mass fraction is then multiplied with biomass dry matter to reveal the carbon content (IPCC, 2006). Usually, a fraction of 0.5 is applied for simplicity, although the exact value varies within a small range for different species and plant components (Ravindranath and Ostwald, 2008). In order to avoid unnecessary work and costs the inventories could be reduced to those biomass components (i.e. carbon pools), which are expected to change significantly. In the case of an afforestation project, the carbon pool of understory vegetation, for instance, might be changing only slightly, whereas tree biomass but also soil organic carbon might change remarkably in case the initial amount of soil organic carbon is low (Pearson et al., 2007).

Living above-ground biomass

Living above-ground biomass of a forest can be classified into trees and understory vegetation (especially herbaceous vegetation and shrubs). Understory vegetation can be inventoried by destructive sampling in small plots. Thereby, the harvested plant material is pooled by plot to give a composite sample, weighted, and then oven-dried to determine dry-to-wet mass ratios, upon which the oven-dry mass is calculated. In comparison, tree biomass can be estimated by allometric methods or terrestrial laser scanning (TLS).

Allometric methods

Most inventories of above-ground biomass are utilizing allometric equations to relate simple, manually measured tree attributes to biomass and other attributes which are more difficult to measure. At the minimum, tree diameter at breast height (DBH) and the species have to be recorded. Adding height measurements of at least some trees considerably improves the predictive performance of allometric equations (Sullivan et al., 2018). Allometric equations make use of the fact that each tree species grow in a predictable manner and the size of the plant organs are proportional (FFPRI, 2012). The relationship between forest tree diversity and carbon storage needs to be considered when choosing an allometric equation on within-stand level (Sullivan et al., 2017). However, on stand level it might be sufficient to choose the equation to suit the forest type (e.g. evergreen or deciduous) and the environmental conditions in the region. Existing allometric equations should be used as far as possible, as the development of own allometric models, which conventionally requires destructive sampling of the sample trees, is labour-intense and expensive (Liang et al., 2016). Forest inventories are typically based on several permanent sampling plots representing a small forest area (e.g. circular in shape with a radius of 4 m to 15 m, Liang et al., 2016). The size and number of the plots is a trade-off between feasibility and measurement uncertainties. The manual tree-by-tree measures, most often taken by simple tools such as calipers and clinometers, are aggregated to plot-level means and totals.

Terrestrial laser scanning

Forest inventory attributes can be further estimated by TLS, which is based on ground-based Light Detection and Ranging (LiDAR). Pulsed laser light is fired from a certain position into the surrounding forest and the time it takes for the pulse to bounce back is measured. This allows to calculate the distance to the object, in this case the nearby trees and understory, and by repeating this the above-ground biomass of a certain area (plot) can be mapped automatically, three-dimensional and in high accuracy (millimeter-level; see e.g. Liang et al., 2016). Comparisons with allometric methods allow for the validation of both and the detection of potential biases. In consequence of its advantages and a broader set of attributes that can be covered as with manual measurements, TLS is expected to become operational within forest inventories with the development of respective software and best practices. Similar terrestrial point cloud data (data in form of 3d point clouds specifiying the tree surface) as with TLS can be captured with mobile laser scanning, personal laser scanning, and image-based point clouds.

The amount of labour-intense field work to estimate the living above-ground biomass can be reduced by utilising remote sensing (see section 2.2.5), which can either completely replace (after initial ground truthing) or be combined with the plot-based sampling in the field.

Dead above-ground biomass

Litter and deadwood typically contribute only a small fraction (< 10 %) to the biomass of forests and plantations, which is potentially removed from the forest for fuelwood. Litter and deadwood can be quantified in the same way as the understory vegetation and sampled in a line intersect, respectively (Ravindranath and Ostwald, 2008). Alternatively, the carbon stocks in these pools can be accounted as a fixed percentage of the above-ground living tree biomass (UNFCCC, 2015).

Below-ground biomass

In comparison to above-ground biomass, quantifications of below-ground biomass (coarse and fine roots) are less well established and standardised. Root biomass is most often not distinguished between live and dead roots. The required destructive sampling is done by excavation of tree roots (as monolith for deep roots) and soil cores or pits for non-tree vegetation. For afforestation projects, the labour-and cost-intense measurements of below-ground biomass are typically replaced by calculations as a proportion or function of the above-ground biomass pool, using information on root/shoot ratios mainly in form of Biomass expansion factors (BEFs; e.g. Lehtonen et al., 2004) or allometric equations such as proposed by Cairns et al. (1997) or Mokany et al. (2006) (Ravindranath and Ostwald, 2008). Putting emphasis on accurate measurements of the above-ground biomass allows to accept the uncertainties of estimations for the below-ground biomass.

2.2.1.2 Soil

Although soil organic carbon is likely to accumulate during afforestation projects, the annual stock increment over the reference state (stocks measured during the initial vegetation and soil carbon inventory before afforestation) is small, and therefore difficult to measure and of high uncertainty (Ravindranath and Ostwald, 2007; Aubinet et al., 2012).Whereas remote sensing can be helpful for inventories of carbon in biomass, soil organic carbon is dependent on labour-intense fieldwork, where soil samples (cores) are taken and individually analysed. The specific sampling design has to be a trade-off between practical feasibility, minimal soil disturbance and statistical power. The detection of statistically significant rate changes depends on the inherent within-site variability of the soil carbon content, the depth increment considered, the number of sample plots and the representativeness of the spatial sampling design with regard to soil properties (Arrouays et al., 2018, Schrumpf et al., 2011). The statistical methods applied to quantify the average change over the area of interest are of importance and have to be chosen according to the sampling design. The time needed for detectable changes in soil organic carbon stocks depends is reported to correspond to approximately ten years (Schrumpf et al., 2011).

Soil sampling is conducted either with the core/cylinder method (non-stony soils) or the excavation method by digging a pit (stony soils) and cover, for instance at ICOS ecosystem sites, 1 m depth with decreasing increments towards the soil surface as this is sufficient to capture most of the detectable changes over decadal periods (Arrouays et al., 2018). Simultaneous measurement of soil organic carbon content and bulk density enable to avoid biases linked to the correlation between both. Sample processing differs between mineral and organic soil samples. Methods available for the analysis of the soil samples comprise simple laboratory estimations to diffuse reflectance spectroscopy, with wet digestion or titrimetric determination (Walkley and Black method) as the most common cost-effective method.

2.2.1.3 Uncertainties of forest carbon inventories

Measurement uncertainties in forest inventories are related, e.g., to the quality of manual field samples, which can be estimated by replication. Liang et al. (2016) concluded that TLS measurements provide accurate enough data for forest inventories, except tree height estimations, for which uncertainties are not yet acceptable. Measurement uncertainties for living aboveground biomass can further arise from the choice of allometric equations and account typically for a few percent. More specifically, these uncertainties represent modelling uncertainties, which also emerge in case remote sensing (e.g., satellite images, aerial photos, LiDAR, see section 2.2.5) is used, as the raw remote sensing data needs to be translated into forest parameters. With the help of quality control samples the variability in the residuals and potential directional bias can be calculated as difference between actual and modelled values. In case an inappropriate or less appropriate equation is used only at one site, the systematic error turns into a random error. Uncertainties related to living above-ground biomass measurements are propagated in case below-ground or dead above-ground biomass are calculated as ratio of it. Furthermore, applying a generalised estimate of 0.5 for the carbon mass fraction induces additional systematic measurement uncertainties.

Sampling and representativeness uncertainties depend, e.g., on the number and location of the inventory plots (and the stochastic model on which the spatial sampling scheme based) or the footprint of the satellite image, as well as on the heterogeneity of the stand (structure and species) or soil. The samples should be representative for the whole stand, also when using them to train a remote sensing model. To estimate the sampling uncertainty the standard error can be calculated. The representativeness uncertainties can be minimised by using a statistically valid sampling design.

Utilising remote sensing typically reduces the sampling uncertainty (and the amount of work) at the expense of a higher measurement (modelling) uncertainty. Careful consideration of the different sources of error help to make informed decisions, e.g., when it is worth to include remote sensing and to which degree.

Monni et al. (2007) estimated for 2003 a carbon sink for Finnish forest vegetation and soil of 12 ± 12 Tg CO_2 and 8 ± 7 Tg CO_2 for 2003, respectively. Due to improved methodology the current uncertainty estimate of forest sink in Finnish greenhouse gas inventory is ±31% (NIR 2018).

2.2.2 Chamber techniques

A chamber generally encloses the compartment of interest such as a leaf or branch or a certain tree stem or soil surface area (typically < 1 m^2). It is equipped to measure the gas (particularly CO_2, but also CH_4 and N_2O) concentration change within the chamber, based on which the gas exchange between the compartment of interest and the atmosphere is calculated. The chamber technique is particularly well-suited for laboratory-based and in-situ process-level studies (Pavelka et al., 2018).

Chambers are typically classified into steady-state, where the gas flux is calculated under constant gas concentration in the chamber, and non-steady-state, where the gas flux is calculated from the rate of change in the gas concentration within the chamber (Rochette and Hutchinson, 2005). Both classes have their individual advantages and disadvantages and can be further divided into flow-through and non-flow-through systems in dependence on whether air is circulated through the chamber or not. The non-steady-state non-flow through soil chamber, from which air is sampled into vials and analysed in the lab by gas chromatography, is a rather outdated system but still in use due to their independence on power supply, particularly at remote sites. In case of sufficiently low vegetation, transparent soil chambers facilitate measurements of whole ecosystem NEE. In combination with opaque chambers, measured NEE can be separated into GPP and R_{eco}. For CH_4 and N_2O typically opaque chambers are used.

Flux calculation can be done following distinct schemes, differing in their theoretical basis and numerical requirements (Pavelka et al., 2018). A standard and robust scheme is a simple linear regression, which, however, may result in small flux underestimations due to non-linearity of the concentration change (e.g. Pihlatie et al., 2013). Auxiliary measurements required for flux separation into GPP and R_{eco}, gapfilling and temporal upscaling comprise air temperature, soil temperature, soil moisture and photosynthetically active radiation (PAR) in case of transparent chambers.

As for all in-situ measurements, the specific measurement locations have to be selected carefully. Replications are necessary for chamber measurements in order to represent the spatial heterogeneity of the area to be monitored. Spatial heterogeneity needs to be considered when upscaling this plot-scale measurement to a larger area. In forests, chambers are only applicable during the first years after afforestation, when the seedlings still fit into the chambers, or for observations of the gas exchange of forest understory and soil. However, chambers are in most cases not suitable for long-term or large-scale carbon stock change observations, at least not as the primary method. Besides the limited amount of plots and the tiny area they cover, resulting in high sampling and upscaling uncertainties, they disturb the object being measured, especially when it comes to photosynthesis. Thereby, systematic measurement uncertainties arise, e.g., from biological and physical disturbance related to the soil collar placement and measurement process (e.g., the chamber is blocking the wind). Ilvesniemi et al. (2009) show how upscaling matches with observations by eddy covariance and inventories over several years at one site. Even though automated, quasi-continuous chamber measurements are not optimal for monitoring purposes, manual (labour-intense) soil chamber surveys can complement, e.g., eddy covariance measurements, investigating the spatial heterogeneity of GHG fluxes. In general, chamber measurements should cover seasonal changes and events such as fertilisation. A protocol for standardised soil chamber measurements was recently developed for ICOS stations (see Pavelka et al., 2018). Other recommended references include Pumpanen et al. (2004) and Butterbach-Bahl et al. (2016).

Chamber- based flux measurements can be combined with several other biometric methods such as plant growth assessment and repeated stock inventories to get a direct estimation of the component processes of the ecosystem carbon cycle (Campioli et al., 2016). This technique is applicable to almost any site and environmental conditions, which is of great advantage in comparison to the eddy covariance technique and offers potential for an integration of both techniques. However, the approach is too labour-intense for long-term and large-scale monitoring and is characterised by high upscaling uncertainties, as biometric measurements are typically performed on few replicated individuals and plant organs or small ecosystem plots. Making linkages between specific weather events and changes in carbon dynamics is complicated by the fact that not all methods can easily be applied continuously. Furthermore, potentially important components of the carbon budget might not be accounted for.

2.2.3 Tower-based eddy covariance flux measurements

The eddy covariance technique is a widely used and one of the most direct and defensible methods for quantifying exchanges of CO_2, CH_4, N_2O, H_2O, various other gases and energy between the surface of the earth and the atmosphere at ecosystem scale. It is based on determining the turbulent vertical transport of matter and energy at a certain measurement height above the ecosystem, typically averaged over a 30-minute period. In a ground-based setup, sensors are mounted on a tower or tripod for measuring fluxes over the surface. The quasi-continuously measurement system imposes minimal disturbance on the environment once operational. Eddy covariance measures the gas exchange on ecosystem-scale and requires a minimum area of homogeneous land cover in dependence on the size of its footprint (source area of the flux). The total upwind distance represented by tower can be estimated based on the 100 to 1 fetch-to-height ratio as a rough ‘rule-of-thumb’ (Burba, 2013). The strongest contribution originates from about 10 times of the measurement height. In addition to the measurement height, the exact footprint depends on surface roughness and atmospheric stability. The setup should be installed well above the canopy, however, installing it too high will result in a violation of the underlying assumptions on turbulent transfer and the source area becomes more uncertain as the "tail" of the footprint distribution can extend kilometres away.

The eddy covariance technique features continuous monitoring with high temporal resolution and a sampling area well suited for the scale of ecosystem-level estimates. Measurements are routinely conducted since the 1990s, providing long-term, continuous flux measurements at a variety of sites and biomes in different climatic zones. FLUXNET, a global network of regional eddy covariance flux tower networks considerably improved the standardization of the data acquisition, processing and provision since the early 2000s (Baldocchi et al., 2001). State-of-the-art protocols for standardized eddy covariance measurements and data processing are provided by ICOS (Rebmann et al., 2018, Sabbatini et al., 2018, and Nemitz et al., 2018). Observations at remote areas without grid power might require individual setup solutions, which, however, should be as close as possible aligned to common standards. Recommendations for further reading are Aubinet et al. (2000, 2012) and Burba (2013), and Urbanski et al. (2007) and Ilvesniemi et al. (2009) on long-term measurements in forest ecosystems.

The basic instruments include a fast-response sonic anemometer and gas analyser. High-frequency and -precision instruments are crucial to accurately determine the flux. Additional measurements needed to achieve high-quality eddy covariance fluxes are air temperature, relative humidity and air pressure. Measurements of net radiation, photosynthetic photon flux density, as well as soil measurements including soil temperature profile and soil moisture/ water table depth are further of value for the interpretation of the fluxes. Depending on the measurement height above the ground and the time scale considered, it might be important to include storage flux measurements to the eddy covariance setup (Montagnani et al., 2018). Cautious and standardised post-processing of the raw flux measurements is essential for the reliability and intercomparability of the observations and should include footprint modelling to estimate the source/sink area of the measured fluxes. With regard to CO_2, specific algorithms can help to separate the measured NEE into GPP and TER (see e.g. Reichstein et al., 2005). It is one of the important drawbacks of eddy covariance, that these two main components need to be estimated indirectly by post-processing. Another drawback is that advective and low-frequency flows of gases, which are particularly important in case of variable topography, are difficult to capture and might result in an underestimation of fluxes during periods with low air turbulence (as typically for ecosystem respiration at night) (Campioli et al., 2016).

Systematic uncertainties can be minimized with an optimal measurement setup (including the measurement height and the location of the tower, also determining the characteristics of the flux footprint) and standardized post-processing of the eddy covariance raw data, making the random uncertainty of the fluxes (e.g., related to precision limitations of the instruments) to the dominant uncertainty at short timescales. Random uncertainties are getting particularly important for the interpretation of small fluxes in terms of turbulent exchange or signal-to-noise ratio (SNR) of the instrumentation, and the role of the ecosystem as source or sink might be unclear. They can be estimated in total for each averaging period as well as separated into its main components such as instrumental noise and the one-point sampling error (Rannik et al., 2016). Estimates for systematic and random uncertainty of eddy covariance derived carbon budgets, e.g., on annual scale are available in the literature. The annual random uncertainty is typically < 50 gC m^{-2} depending on the flux magnitudes, whereby larger fluxes bear larger uncertainties. Richardson et al. (2006) reported an annual random uncertainty in the order of 20 gC m^{-2}. Moffat et al. (2007) calculated a gapfilling uncertainty of the same magnitude, whereas Gielen et al. (2013) report very large uncertainty based on turbulence filtering and gapfilling, which might be related to a very high carbon sequestration during one year. Estimating the systematic uncertainties is not trivial as it requires independent reference data which in turn have their own systematic and random errors. Studies comparing eddy covariance flux measurements with other methods such as inventories are: Black et al. (2007) and Campioli et al. (2016). The ballpark estimate for NEE systematic uncertainty is typically about 10-20%. Eddy covariance-based estimates of carbon sink strengths are rather a slight overestimation rather than underestimation, as daytime flux measurements (net uptake) are less prone to errors than night-time fluxes (efflux). However, this implies that there are no issues with footprint heterogeneity. GPP and TER systematic uncertainties are larger than for NEE due to the additional uncertainty of the partitioning process, whereas the random error is of the same order as for NEE (e.g., ranges of partitioned fluxes in Desai et al., 2008). GPP and TER should only be used as tools to understand the dynamics of the carbon balance, not as absolute budgets.

2.2.4 Large-scale atmospheric GHG concentration measurements

Atmospheric GHG concentration measurements are spatially integrating measurements and, thus, mixed signals of different GHG sinks and sources including fossil fuel emissions. For large scale observations, platforms for continuous monitoring and flask sampling are, for instance, continental stations (tall towers specifically built for this purpose or existing television, radio and cell phone towers, see e.g. Timokhina et al., 2018), mountain and coastal stations and airborne platforms (aircrafts, helicopters). The source area of an atmospheric measurement is increasing with the height at which the air is sampled and can be on the order of 100 km. Thus, the source area is considerably larger compared to eddy covariance flux measurement.

Close proximity (< 40 km distance) to strong anthropogenic sources such as cities should be avoided especially if located upstream of the prevailing wind (unless particularly the emissions of these cities are of interest), to make sure that the observations can be represented in atmospheric transport models of certain spatial resolution.

For automated in-situ measurements, air is sucked by a pump and passed through one or several gas analyser/s. High precision measurements are needed in order to accurately capture the atmospheric signal which is smoothed out during the transport in the atmosphere. For example, for CO_2 concentration an accuracy of 0.1 ppm is necessary in remote areas to facilitate the detection of spatial patterns against the background concentration. Auxiliary measurements required are air temperature, relative humidity, wind direction and speed (needed for the calculation of the source area), atmospheric pressure as well as planetary boundary height, which is of specific importance for atmospheric inversion modelling (Kretschmer et al., 2012).

At ICOS stations, an accuracy as defined in the GAW report n° 213 (https://library.wmo.int/pmb_ged/gaw_213_en.pdf) of the World Meteorological Organization (WMO) is required, however, over an extended concentration range as given in the report. For the estimation of source distributions on regional scale, observations from a distributed network of stations and regional land cover maps are required. An optimal distribution of ICOS measurement stations, aiming to avoid large spatial gaps, was yielded from a thorough network design assessment including footprint simulations. The atmospheric station network of ICOS comprises continental, coastal and mountain stations, targeting predominantly continental air-masses, marine air-masses and free tropospheric air (during night), respectively. The standardised specifications for atmospheric GHG concentration measurements within ICOS are available at: https://icos-atc.lsce.ipsl.fr/filebrowser/download/27251. Standardised measurement protocols and calibration procedures are crucial for assimilating measurements at various stations, e.g. for the validation of climate models and the reduction of their uncertainties, and as input for atmospheric inversions (section 2.4.2). Additional periodic measurements with independent methods, such as the analysis of flask samples with gas chromatography, should be performed to reduce the risk of a systematic bias in the observations. The inclusion of stations in international inter-comparison programs facilitates compatibility with other international networks such as the WMO GAW.

Campaign-based airborne measurements of atmospheric GHG concentrations (e.g. NASA's Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE; https://daac.ornl.gov/CARVE/guides/Alaskan_CH4_CO2_Fluxes.html) are of particular advantage for observations in remote areas, where the setup of a ground-based station is impossible, for instance with regard to power supply. In case the gas concentration measurements are conducted at high frequency, the measurements can, in combination with three-dimensional wind measurements, be used for GHG flux calculations (see section 2.2.3; e.g. Kohnert et al., 2017). The use of commercial aircrafts as done by the European research infrastructure IAGOS (In-service Aircraft for a Global Observing System) allows global observations of atmospheric GHG concentrations on a periodic basis.

Large scale atmospheric GHG observations might be useful for a rough estimation of the carbon storage change in case the area of interest such as the afforested area is sufficiently large to represent a considerable part of the footprint.

2.2.5 Aircraft and satellite remote sensing

There are several ways how remote sensing can support the quantification of forest carbon storage and its changes on different spatial scales and new techniques are progressively developed (see https://earthdata.nasa.gov/user-resources/remote-sensors for an overview on sensor types). However, it is not suitable as stand-alone method as it requires ground-truthing. Spectral, spatial and temporal resolution are important attributes of remote sensing data, determining their uncertainties (see Matese et al. 2015 for typical attributes of different approaches, also section 3.2.2). Combining datasets retrieved in different spatial and temporal scales by different satellites helps to refine the resolution of the remote sensing products. It has to be kept in mind, that satellites provide snapshots only, which might even be affected by cloud cover (Sims et al., 2005).

Remote sensing of the land surface and the elaboration of these data to regional and global land cover maps and vegetation indices such as leaf area index (LAI) are particularly useful for the upscaling of plot-, ecosystem- and landscape-scale GHG flux measurements to regional and global scales (section 2.4.1). Thereby, Landsat represents the longest continuously acquired collection of satellite-based, moderate-resolution data. However, based on a combination of various land-surface datasets even more advanced data products can be yielded, such as estimates for primary production of the global vegetated land surface over an 8-day interval at 1-km resolution (Heinsch et al., 2006; based on meteorology, land cover and LAI).

Remote sensing, e.g. with airborne and satellite-based LiDARs is further very helpful for inventories of above-ground biomass, e.g. by mapping the spatial distribution of canopy characteristics, and can substitute labour-intense field work (see e.g. Muukkonen et al., 2006; Popescu et al., 2011). Field surveys of these variables should be used as ground-truths. Within the EU project "North State" (https://cordis.europa.eu/result/rcn/201350_de.html) a method was developed to infer the forest carbon balance from land cover and forest variables such as wood biomass and tree species predicted with satellite image data of Sentinel missions as part of the Copernicus program (Earth observation programme of the European Union), supported by Landsat satellite data. Image analysis was done by self-learning and intelligent tools being able to analyse big data. The combination of land cover and forest variables with specific forest growth models resulted in detailed maps of carbon sequestration in boreal forests.

Apart from generating canopy maps, the LiDAR technique is further capable to profile GHG gas concentrations and wind velocity along the lidar line of sight or in 2D or 3D (Gibert et al., 2011), allowing for airborne (and ground-based) flux measurements by means of the eddy covariance method.

Aircrafts and satellites can be further utilised as platforms for indirect measurements and large-scale mapping of GHG concentrations averaged over the atmospheric column between the Earth´s surface and the observation platform. Thereby, airborne remote sensing systems such as the Methane airborne MAPper (MAMAP, CO_2 and CH_4) fill the gap in spatial resolution between ground-based and satellite-based measurements of atmospheric composition and are particularly helpful for the detection of surface sources of GHGs. The measurements are revealed by comparison of direct sunlight and sunlight backscattered to space measured by spectrometers at different wavelengths. Prominent examples for such solar backscatter instruments on board satellites are the European Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY; CO_2 and CH_4) instrument on board ENVISAT, the US-American Orbiting Carbon Observatory-2 instrument (OCO-2; CO_2), TANSO-FTS on board Japan's Greenhouse Gases Observing Satellite (GOSAT; CO_2 and CH_4) and the European TROPOspheric Monitoring Instrument (TROPOMI; CH_4 and N_2O) on board the Copernicus Sentinel-5 Precursor satellite, which was launched as the first of the atmospheric composition Sentinels.

2.2.6 Modelling approaches

2.2.6.1 Modelling dynamics in aboveground biomass and respective carbon stocks

The number of modeling approaches used in forest related questions is enormous (cf. Barredo et al. 2012, Charru et al. 2017, Nabuurs et al. 2018). The range covers from traditional empirical stand level models (e.g. MOTTI, Hynynen et al. 2002) to the Dynamic Global Vegetation Models (DGVM) which are complex process-based ecosystem models which could be used as a module in a fully coupled system connecting vegetation to atmosphere (Nishina et al. 2015). Between these extremities there are regional data-driven models (MELA, MONSU, EFISCEN) and a bit more complex models like CBM-CFS3 (Kull et al. 2016); CO2FIX (Schelhaas et al. 2004); ForClim (Gutierrez et al. 2016); EFISCEN (Schelhaas et al. 2007, Verkerk et al. 2019), or models approaching mechanistic description of the most processes in the model (e.g. PREBAS Valentine and Mäkelä, 2005, Peltoniemi et al. 2015, Minunno et al. 2016, Minunno et al. 2019, 4C model Lasch-Born et al. 2015). The DGVMs are the most generalized and thus could be used to predict forest growth in large regions (e.g., ORCHIDEE-CAN Naudts et al. 2016; PnET-CN Peters et al. 2013, JSBACH applied to Finnish forests in Peltoniemi et al. 2015; JULES Harper et al. 2016; CLM oleson2010). Both DGVMs and models like PREBAS and 4C could be applied conditions outside of which they were parameterized, such as changing climate and CO2 concentration.

The selection of the used model in specific projects depends on the purpose of model use and especially the scale of the project. The empirical models parameterized for the species and conditions of the region usually provide the most accurate estimates. However, they could not be used in changing conditions and without proper data for parameterization. In this kind of situation, process based model could be applied. Depending on the level of how 'process based' the model is there is higher degree of freedoms for application outside the original parameterization. However, all these models have parts which are more or less semi-empirical and their behavior depends on the parameterization. Important general aspect to keep in mind in forest models is that no model is better than the data used for it (parameterization-validation-calibration). Models could be used in synchrony with the measurements to fill the gaps of the measurements, move from the one scale to another and as tools to cover discontinuities. Mechanistic models enable to address questions otherwise difficult/impossible to formally quantify.

Good example of large-scale complex model is ORCHIDEE-CAN, which takes climate data based on the latitude and longitude of the pixel to compute the amount of carbon assimilated by groups of identical trees of different diameter classes at 30-minute intervals. At the end of every day, this carbon is allocated to different pools representing various parts of the tree (roots, sapwood, and leaves), and the various pools undergo turnover to convert the carbon into other pools (such as hardwood and litter). Once a year, the grid square can undergo management, wherein woody biomass is removed from site. The model thus stores the amount of carbon available in each of the pools at daily resolution. ORCHIDEE-CAN can also simulate tree species instead of more generic plant functional types. Like some forest-specific models, ORCHIDEE-CAN does not recognize the horizontal spatial arrangement of vegetation within a pixel, though it does recognize vertical distributions. While simplified, ecosystem models share many of these concepts, depending on the specific model. Some ecosystem models can be coupled directly to atmospheric circulation models, providing insight into forest growth at large scales and the resulting climatic impact; such models are often called ``land-surface models'' and generally contain less complexity (in terms of processes included and their descriptions) than stand-level ecosystem models.

Nowadays there are approaches where process based model is coupled with satellite data to derive both the parameters of the model and input data for the description of the initial state of the forest. Future development of the forest depends on the processes of the model. Pixel size of the model projections can vary from several square kilometers to the tens of meters (Fig. 2.2). These approaches are under rapid development. Application costs of these approaches depend on the specific objectives of mitigation project e.g. needed time and spatial resolution.

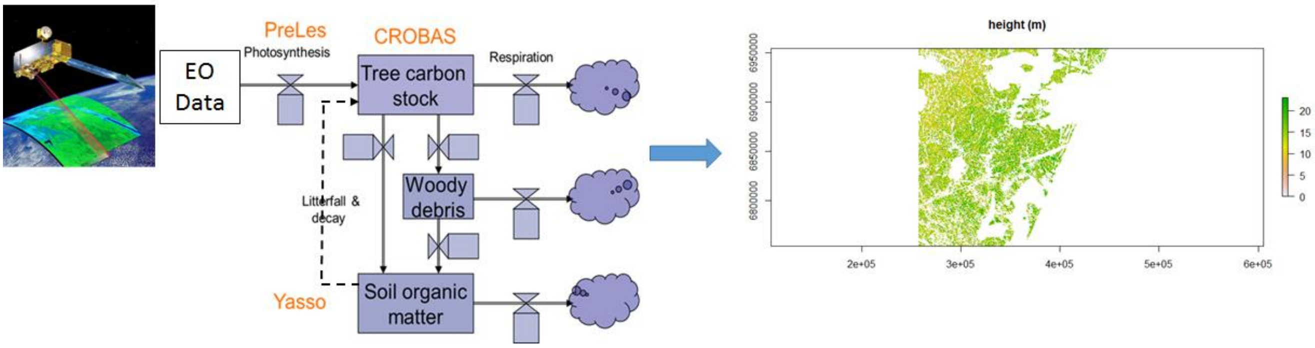

Figure 2.2 The model approach used in North State project (http://www.northstatefp7.eu/). Satellite data (EO = Earth Observational) was used for deriving initial state of PREBAS model. Detailed maps of high resolution (e.g. 20 m x 20 m of forest height here) were produced with PREBAS. Courtesy of figure: Annikki Mäkelä, Francesco Minunno, Tuomas Häme.

2.2.6.2 Modelling changes in soil organic carbon stocks

Due to the great spatial variation together with the laborious and expensive nature of collecting field samples (Mäkipää et al. 2008), there are numerous efforts to model soil organic carbon dynamics. First models of soil biogeochemical processes were drafted already in the 1930s (Salter and Green, 1933; Nikiforoff, 1936), and today there are various stochastic, empirical and mechanistic models featuring soil carbon dynamics with varying terms of complexity and biological processes (Manzoni and Porporato, 2009). In general, the models produce similar carbon stocks, variations and uncertainties as observations (e.g., Ortiz et al. 2013), thus enabling response studies even if there is no data available. However, a variety of observational studies is needed to validate the model performance for different ecosystem types.

Soil carbon models operate on different time steps typically from one day to one year. The amount and chemical characteristics of carbon input as litter are determined by the vegetation and often taken as a measured or modelled input outside the soil organic carbon models. The decomposition rate of soil organic carbon depends on the litter quality, soil temperature, moisture and oxygen availability, soil texture and its chemical properties (Swift et al., 1979, Chapin et al., 2011). Therefore, a selection of these are the most often used drivers for the modelled biological, chemical, and physical transformations in soils. As there is increasing evidence of the significance of microbial litter playing a key role in the stabilization of soil organic carbon (Kallenbach et al. 2016), the dynamics of microbial litter and the interaction between microbes and mineral particles are currently introduced to soil organic carbon cycling models. The required number of parameters and variables increases with the model complexity whereas the information on soil characteristics and other input variables may be limited in many cases. On the other hand, the complex process-based models may simulate the most accurate responses for example to changing environmental conditions.

One of the most widely used models include CENTURY (Parton, 1987), RothC (Coleman and Jenkinson, 1996) and ECOSSE (Smith et al. 2010) but these models are conceptual without measurable soil organic carbon pools. In comparison, the YASSO model (Tuomi et al. 2009, 2011) follows IPCC guidelines and fulfils UNFCCC requirements and it is used for example in Finnish national carbon inventories as well as in the JSBACH model (Goll et al. 2015), a land component in the MPI Earth System Models MPI-ESM. YASSO describes the decomposition of soil organic carbon by dividing it into five measurable pools based on solubility and thus, it differs from the majority of the soil organic carbon models. The Millennial model (Abramoff et al. 2017) is another, new attempt to model soil organic carbon dynamics with different carbon pools as measurable entities but currently it is not in general use.

2.3 Integrative approaches for reliable regional and global estimates

Quantifications and predictions of carbon and GHG fluxes at regional and global scales are dependent on models, to combine temporally and spatially spread observations. The models are based either on a bottom-up or top-down approach. As forest covers 67 % of the global land area (FAO 2015), reliable estimations of the forest carbon sink are of utmost importance.

Bottom-up and top-down approaches are, for instance, combined within the H2020 project VERIFY (http://verify.lsce.ipsl.fr), aiming to develop a robust and transparent (pre-operational) system for the estimation of greenhouse gas emissions to support national emission reporting. Estimates of CO_2, CH_4 and N_2O emissions are based on land, ocean and atmospheric observations (satellites, ground-based networks, fuel use and emission factors) and in case of CO_2, fossil fuel emissions are separated from ecosystem fluxes. Within the project, the top-down approach delivers the net GHG budget estimates by combining all information available, including bottom-up inventories, which can attribute GHG budgets to sectors and processes.

2.3.1 Bottom-up approach

Bottom-up estimates of regional and global surface-atmosphere net GHG exchange build up on ground-based accounting methods and inventories. For bottom-up flux estimates of terrestrial ecosystems, plot- to landscape-scale GHG flux measurements (particularly by means of eddy covariance as provided by FLUXNET for instance, but also chambers) are assigned to specific land cover, soil or vegetation classes. The fluxes are then spatially extrapolated (upscaled), typically by machine learning, based on emission factors calculated for each class (average flux) and spatially resolved data (maps) on climate as well as land cover, soil properties or vegetation indices derived from remote sensing (section 2.2.5, see e.g. Xiao et al., 2011). Recent studies show that global upscaling of forest NEP from flux measurements using climate and remote sensing alone reveals forests as too large carbon sinks (Jung et al., 2011; Zscheichler et al., 2017; see references also for uncertainty estimation). For more reliable extrapolation of forest NEP, the forest age since afforestation or the last disturbance (e.g. fire, clear-cut) was identified as an important determinant to be considered, as the carbon sink properties of forest stands are changing with age (personal communication with Ville Kasurinen and Philippe Ciais). For this purpose, flux measurements of forest chronosequences have been utilised by Ciais et al. (2018) to define (biome-specific) hypothetical curves of NEP in dependence on forest age which are then used in the upscaling with the help of forest age maps (Amiro et al., 2010). However, especially recently disturbed forests are underrepresented with regard to flux measurements, and the chronosequences are not equally distributed among the biomes, with gaps in the tropics for instance. Nevertheless, it is evident that the carbon compensation period (time after afforestation/ disturbance until the forest switches from a carbon source to a sink) and, particularly, the carbon payback period (time until carbon sequestration equals carbon loss following afforestation/ disturbance) range considerably between biomes (Amiro et al, 2010; Coursolle et al., 2012; Aguilos et al., 2014). The partially long carbon payback periods and related uncertainty of what will happen to the forest in this period hamper some companies offering carbon compensation to include afforestation into their portfolio of projects (e.g., atmosfair, https://www.atmosfair.de.). In practice, long carbon payback time of forest use calls for long enough commitment periods to keep carbon in the storage from which the credits are gained. Moreover, the claimed mitigation impact of the afforestation should be carefully assessed with best available methodology including direct and indirect effects.

2.3.2 Top-down approach

Atmospheric inversion modelling is an established method to receive top-down estimates of surface-atmosphere net GHG exchange on regional and global scale and standardly used e.g. within the Copernicus Atmosphere Monitoring System (CAMS) and in IPCC reporting. Atmospheric inversions estimate surface-to-atmosphere net carbon fluxes on the basis of atmospheric trace gas concentration measurements (see section 2.2.4), a priori knowledge of sources and sinks and an atmospheric transport model, which links sources and sinks to atmospheric observations. Flux information such as airborne or eddy covariance tower-based flux measurements can be utilized for the validation of modelling results. On the other hand, the results of inverse modelling can be crucial to validate national emission inventories.

Continuous and semi-continuous high-precision atmospheric trace gas concentration measurements are used in the inversions. Most atmospheric inversions are done for CO_2, as it is the most important greenhouse gas and the uncertainties in the a priori information are better known than for CH_4 and N_2O. As for bottom-up approaches, for example information on forest stand age can yield an improvement of the inversion results (Deng et al., 2013).

In multi-model comparison studies the regional and global estimates are most often given as a range representing the outcome of several atmospheric inversions, which differ in the type of the atmospheric transport model, set of observations, prior information and flux optimisation technique. The modern atmospheric inversion results can be globally obtained in 1° resolution, and regionally even in higher resolution. The uncertainties of the estimations are heavily dependent on the individual uncertainties and spatial coverage of atmospheric trace gas concentration measurements in particular, but also of the a priori information. Dense observation networks of atmospheric concentrations exist in Europe and North America, whereas gaps are particularly concentrated on the southern hemisphere. In North Africa, a single station measuring atmospheric trace gas concentration is used within inversion modelling, strongly increasing the uncertainties of the estimates for this region (see https://www.esrl.noaa.gov/gmd/ccgg/ggrn.php). Aircraft and satellite based remote sensing of GHG concentrations as done with MAMAP and TROPOMI (see section 2.2.5) is a valuable tool to increase the spatial coverage of observations and to reduce uncertainty in inversion results. Higher spatial observation density enables higher resolution inversions.

For further information, recent developments in atmospheric inversions and uncertainty estimates see e.g. Peylin et al. (2013), Bergamashi et al. (2015, 2018), Kountouris et al. (2018) and Le Quere et al. (2018).

It should be kept in mind that lateral carbon transport (horizontal flow of dissolved carbon) is not observed by GHG exchange observations. In order to compare and reconcile bottom-up and top-down approaches, regionally varying corrections of bottom-up estimates are necessary to account for processes which, e.g., exchange CO_2 with the atmosphere but do not store carbon in ecosystems such as the release of CO_2 from imported and exported biomass, the riverine transport of CO_2 and the carbon being released as non-CO_2 compounds such as volatile organic compounds (see http://www.globalcarbonproject.org/reccap/protocol.htm).

2.4 Forestry field station Hyytiälä as supersite of forest research

The SMEAR II station (Southern Finland, Northeast of Tampere) operated by the University of Helsinki, is located in an upland boreal forest (Scots pine and Norway spruce with understory vegetation) with lakes and small wetlands. The station represents a densely equipped and wired lab for the comprehensive investigation of biosphere-atmosphere interactions and the impact of climate change (see Fig. 2.3), where measurements are operated continuously since 1996. Long-term monitoring of forest carbon storage, which was standardised with the integration of the station into ICOS (the station is officially labelled as Class 1 ecosystem and Class 1 atmospheric station), and individual process studies on various spatial and temporal scales deliver valuable input for carbon and GHG accounting and forest science. The various in-situ observations allow the exemplary quantification of fluxes and storages of atmospheric carbon in boreal forest ecosystems (Fig. 1.2b) and method comparisons (Ilvesniemi et al., 2009). SMEAR II is one of the few sites in Europe with long-term eddy covariance measurements and thus regularly included in large-scale studies such as on the effect of extreme weather events on ecosystem productivity (Ciais et al., 2005). SMEAR II is part of the INAR RI (Institute for Atmospheric and Earth System Research, a Finnish national research infrastructure) and traditionally included in European research infrastructures and global observation networks, apart from ICOS including ACTRIS (Aerosols, Clouds, and Trace gases Research Infrastructure) and FLUXNET. The standardised atmospheric observations contribute further to European and global monitoring systems such as Copernicus and WMO GAW, and are, together with the in-situ GHG flux observations, valuable input for bottom-up and top-down approaches (see e.g. Kadygrov et al. 2015). SMEAR II was further one of the intensive study sites of the FP7 'North State' project (see section 2.2.5). A considerable number of scientific publications are based on the observations gathered at the station, see also Hari and Kulmala (2005), Hari et al. (2012) and https://wiki.helsinki.fi/display/SMEAR/Measurements, https://www.atm.helsinki.fi/SMEAR/index.php for a general overview on SMEAR II and SMEAR stations in general.

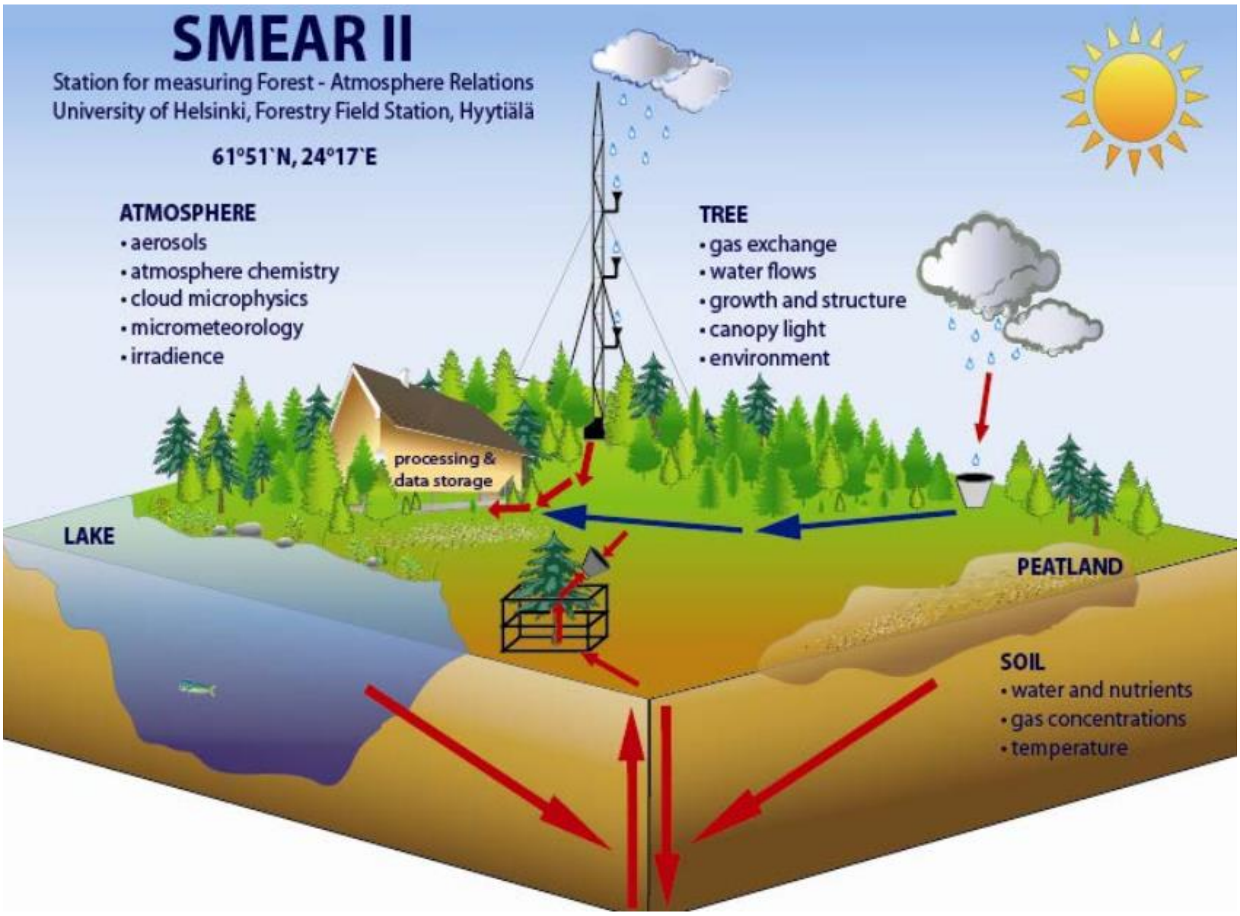

Figure 2.3 Forestry field station SMEARII in Hyytiälä as supersite of forest research

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Sources of pictures for Fig. 2.1:

Pandey et al., 2013 (chambers, tall tower); (shovel) icon made by Freepik from www.flaticon.com; http://www.fao.org/docrep/007/y5490e/y5490e07.htm (tree allometric measurements); Liang et al., 2016 (TLS); https://www.n.ethz.ch/~sewolf/personal/PICS/EC-Method_S.Wolf.png (eddy covariance); https://thenounproject.com/term/drone/14866/ (drone; CC BY 3.0 US); http://chittagongit.com/icon/plane-icon-3.html (airplane); https://thenounproject.com/term/satellite/3485/ (satellite; CC0 1.0)

3. Non-carbon climate effects of forests and how to measure them

Markku Kulmala, Ekaterina Ezhova, Pasi Kolari and Pekka Rantala

3.1 Introduction

The surface temperature of the Earth is determined by the radiation balance between the Earth and the space. The Earth receives electromagnetic radiation from the Sun. Part of the incident radiation is reflected back to space by the atmosphere and the Earth surface, the rest absorbed. The atmosphere and the surface ultimately emit the absorbed energy as long-wave thermal infra-red radiation to the space. Any imbalance in radiation results in warming or cooling of the Earth system.

Besides CO_2 and other greenhouse gases that modify the exchange of thermal radiation between the atmosphere and the surface (greenhouse effect), there are other important factors that contribute to the absorption and reflection of shortwave radiation and the exchange of heat between the atmosphere and the surface (Bonan 2008). Land cover (section 3.2) and aerosols in the atmosphere (sections 3.3 and 3.4) affect directly how much incoming solar radiation is absorbed. Further, they have impact on how heat is distributed between the atmosphere and the surface; evaporation of water from the surface and subsequent formation of clouds in the atmosphere is the most important mechanism here. Any modification of the carbon cycle by removing or increasing CO_2-binding vegetation has impact on the complex climate - carbon cycle feedback (section 3.5).

3.2 Surface albedo

The radiation balance on the Earth surface is the sum of incoming shortwave radiation in the wavelengths emitted by the Sun ($I_{sw,in}$), shortwave radiation reflected off the surface, incoming longwave (thermal infrared) radiation from the sky ($I_{lw,in}$) and longwave radiation emitted by the surface ($I_{lw,out}$)

$$(1 - a)I_{sw,in} + I_{lw,in} - I_{lw,out} = 0$$

where a is the reflectivity (albedo) of the Earth surface in the wavelengths emitted by the Sun. Albedo can range from 0 (black surface that absorbs all radiation) to 1 (perfect mirror that reflects all radiation).

The incoming shortwave radiation on Earth surface depends on the optical properties of the atmosphere, that is, the reflectance of the atmosphere for shortwave radiation (atmospheric albedo). Surface temperature is also modified by the exchange of thermal radiation between the atmosphere and the surface (greenhouse effect). In this section, the direct effect of surface albedo on the radiation balance is considered. Any secondary effects of surface albedo change on the atmosphere are omitted for simplicity.

Decrease in albedo leads to increased absorption of solar radiation by the Earth surface. Long-wave radiation from the surface must increase to match the increased absorption of short-wave radiation to close the energy balance. This can only be accomplished through an increase in the surface temperature.

Surface albedo depends on land cover. Land covered by green vegetation typically has albedo of 0.05–0.28. Increasing vegetation cover usually decreases the albedo. Bare soil albedo ranges from 0.08 to 0.35 depending on soil type and moisture. The albedo of snow is very high, up to 0.95. Typical albedos of different land cover types are summarized in Table 3.1.

Table 3.1 Albedos of different land cover types (Campbell & Norman 1998, Breuer et al. 2003, Hollinger et al. 2010). Perfect mirror reflects all light back, i.e. albedo of it is 1.

Land cover type	Albedo
Snow	0.40–0.95
Dry sand	0.35
Wet dark soil	0.08
Grassland/pasture	0.18–0.28
Savanna	0.16–0.21
Broadleaved forest	0.10–0.20
Coniferous forest	0.05–0.15

Albedo varies seasonally due to changes in surface properties like green foliage area of vegetation. The temporal variability is large especially in regions with seasonal snow cover. For long-term radiation balance calculations one must consider the effective albedo, that is, the average of momentary (e.g. daily) albedo weighted by the momentary incoming radiation.

3.2.1 Climate effect of albedo change

Radiative forcing is widely used metrics for expressing the climate impact of any change in the surface or atmospheric properties that determine the net radiation balance of Earth. It is the net change in the energy balance of Earth expressed in watts per square metre [W m^{-2}]. Positive radiative forcing means that Earth receives more energy from the Sun than it loses to the space. Any change in land cover affects the Earth energy balance directly via surface albedo change and indirectly via other mechanisms that alter the radiative properties of the atmosphere, such as changes in the greenhouse gas, water vapour and aerosol concentrations (IPCC 2013).

Radiative forcing by the albedo change can be estimated directly as the change in the average incoming minus reflected shortwave radiation or as the average incoming shortwave radiation multiplied by the change in the effective albedo. For comparing the direct radiative impacts of albedo change and carbon uptake, we can convert the C uptake to radiative forcing following Harvey (1997). The radiative forcing F [W m^{-2}] that results from changing the atmospheric CO_2 storage C_a [ppm] by dC_a[ppm] is (Betts, 2000)

$$F = 5.35 log\left(1 + \frac{dC_a}{C_a}\right) \tag{2}$$

1 ppm of atmospheric CO_2 corresponds to 2.123 Gt C and the earth surface area A is 5.1 10^{10} ha. The marginal radiative forcing from changing the surface carbon storage by dS [tC ha^{-1}] is

$$F = \frac{-128.521\, dS}{C_a} \tag{3}$$

where 128.521 W ha t^{-1} m^{-2} is the conversion of one tonne of carbon per hectare to radiative forcing units.

Increasing carbon storage with afforestation decreases the radiative forcing through decrease in atmospheric CO_2 which in turn cools the Earth surface. However, afforestation also changes the albedo of the surface. Afforested sites are often originally open pasture or grassland with more reflective vegetation cover than in forests. The change in the annual shortwave radiation balance can be significant and comparable to the radiative forcing caused by changes in carbon storage (Fig. 3.1). In other words, considerable storage of carbon in the vegetation may be required to offset the albedo change. On the other hand VOC, aerosols and clouds will help a lot, and at least in boreal conditions will counteract, at least partly, the albedo effect.

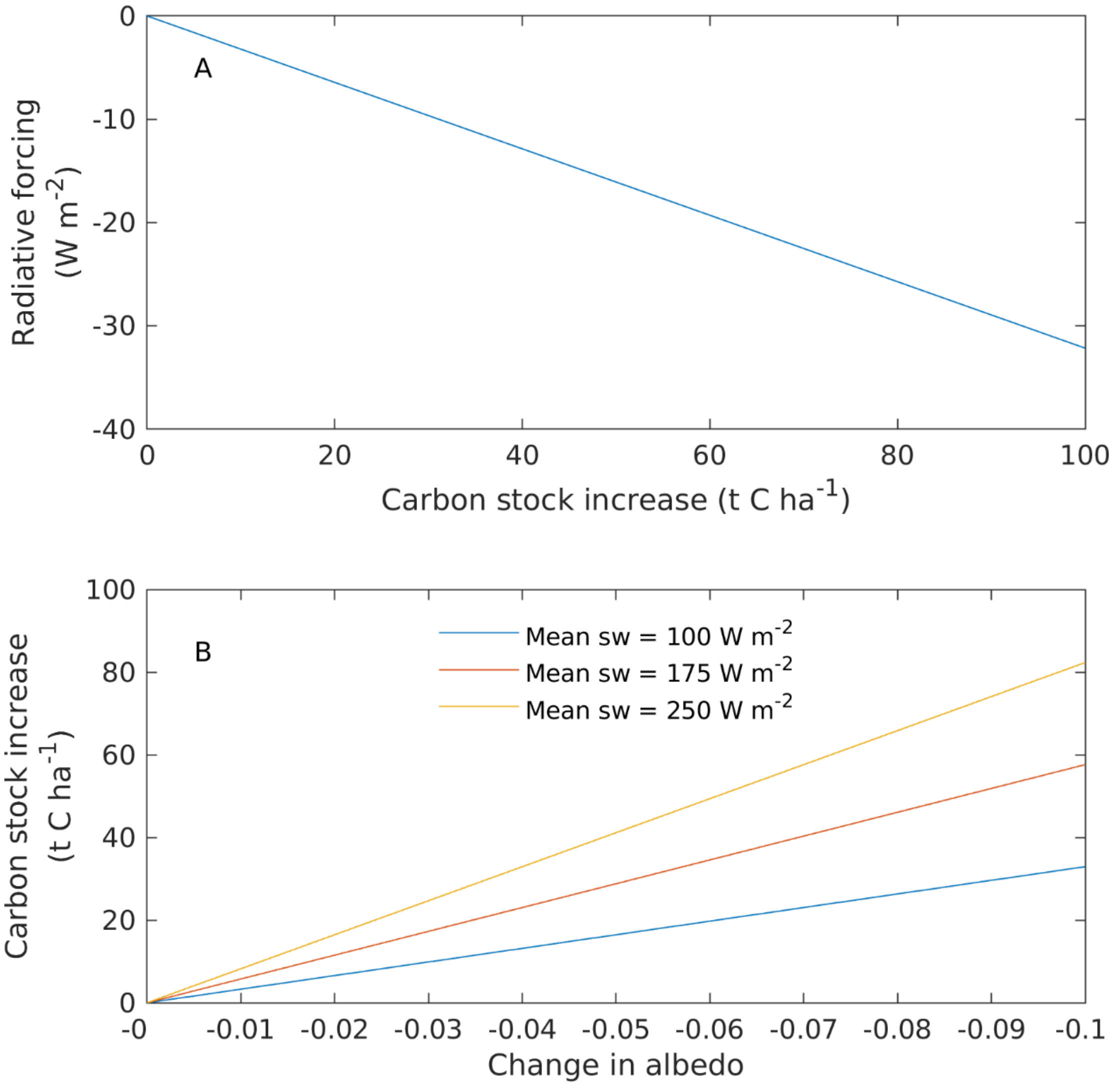

Figure 3.1 Radiative forcing as a function of CO_2 taken up from the atmosphere per unit land area (A), and carbon sequestration required to compensate the warming effect of decreasing albedo at three different values of mean annual shortwave radiation (B). The annual radiation inputs in ascending order correspond roughly to boreal high latitudes, temperate or subtropical zone and tropical zone. The conversion of C uptake to radiative forcing was taken from Harvey et al. (1997) assuming atmospheric CO_2 mixing ratio of 400 ppm. Only the direct effects of atmospheric CO_2 and surface albedo on the radiative balance of Earth were considered.

The climate benefit of afforestation depends on the carbon storage potential of the site, the resulting change in albedo, and long-term radiation input. It may even become negative at locations with extended snow cover or poor growth potential of trees (Brovkin et al. 1999, Betts 2000, South et al. 2011), for instance in the cold climate of the high latitudes or in arid locations elsewhere.

Carbon taken from the atmosphere must be stored in persistent biomass to cancel out the warming effect of albedo decrease. The magnitudes of the carbon storage and albedo decrease depend on time scale and should be integrated over the whole rotation time of a forest stand. The contribution of later growth stages is important as the carbon accumulates and the cooling effect of stored carbon becomes greater than the warming albedo effect.

Land cover changes also alter radiative forcing via other mechanisms, especially through the hydrological cycle. These effects are more uncertain and more difficult to quantify than the direct radiative effects of changed surface reflectance and atmospheric CO_2 (IPCC 2013). When very large areas are considered, the feedbacks between the vegetation and the atmosphere become increasingly important and may offset the direct impact of surface albedo change (Bala et al. 2007).

3.2.2 Quantifying albedo and shortwave radiation balance

3.2.2.1 Ground-based measurement of incoming and reflected shortwave radiation

Albedo and shortwave radiation balance can be measured with two radiation sensors (pyranometers) that detect the wavelengths emitted by the Sun. One sensor is pointing to zenith while the other is looking in the opposite direction, towards the ground. The setup must be installed high enough to capture the small-scale heterogeneity in the surface properties and vegetation. As a rule of thumb, the radius of source area is three times the height above the top of the vegetation. Accurate levelling of the sensors is also crucial (Carrara et al. 2018).

Monitoring of albedo and radiation balance with ground-based measurements provides continuous real-time data that reveals the short-term and seasonal variability in the radiation balance. Typical accuracy of long-term radiation balance measured with pyranometers is 5–10% which translates to accuracy in the order of 0.01–0.02 in the measured albedo. Setting up the measurements and data acquisition requires engineering skills. Maintenance, service, calibration and possibly guarding of the measurement setup requires labour continuously which can make continuous monitoring of radiation balance on the site inpractical.

3.2.2.2 Remote sensing

Another method to determine albedo in the long term is remote sensing by satellites. Spatial resolution in satellite images ranges from 30 m to several kilometres. Temporal resolution is governed by the orbits of the satellites, usually it's days or weeks. Presence of clouds disturbs the determination of surface reflectance and leads to sparser temporal coverage of useful data. Satellite data are often tradeoff between spatial and temporal resolution. Estimates of surface properties in finer resolution can be obtained by fusion of datasets retrieved in different spatial and temporal scales by different satellites, for instance Landsat albedo in 30 m grid and more frequently obtained surface reflectance data such as MODIS datasets in 500 m resolution (Qu et al. 2015). Besides surface reflectance, estimate of local incoming solar radiation and its seasonal variability is needed for calculating the radiative forcing caused by changes in albedo. One option is to use empirical models that predict the daily solar radiation as a function of maximum and minimum daily temperature or other local ground-based meteorological observations (Moradi et al. 2014). Another option is combining different satellite data products (Zhou et al. 2017). The accuracy of these approaches for the long-term mean or cumulative incoming radiation is in the order of 10%.

Remote sensing data products require little field work on the site of interest as many data products are freely available in the internet. However, processing and analysis of data requires good mathematical and programming skills. Furthermore, the accuracy of the remotely sensed data should be evaluated with repeated ground-based characterization of vegetation structure and measurements of albedo. This is especially important if the landscape is heterogeneous, consists of small patches of different land cover types or has steep slopes. The accuracy of remotely sensed albedo can be as good as in ground-based measurements if the landscape is homogeneous (Cescatti et al. 2012).

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3.3 Volatile organic compounds

Volatile organic compounds - usually referred as VOCs - are a wide group of different hydrocarbons that can evaporate rather easily in normal room conditions, meaning that they are volatile in the standard pressure (1013 mbar) and temperature of around 293.15 K (20°C). The number of different VOCs is enormous as carbon and hydrogen can form so many different structures. In addition to carbon and hydrogen, a VOC can contain also for example oxygen and/or nitrogen.

In the atmosphere, VOCs are trace gases due to their low concentrations, meaning usually less than 1 ppb (parts per billion) or even less than 1 ppt (parts per trillion) depending on the compound. Major part of the VOCs originates from vegetation, such as tropical and boreal forests, whereas anthropogenic – i.e. human-produced - VOCs originate from the traffic, industry and solvents, such as paint thinners.

From the point of the atmosphere, VOCs are important because they affect the atmospheric boundary layer chemistry and aerosol particle formation. Thus, they are also linked to cloud formation and air quality. Globally, the most important VOCs are isoprene and monoterpenes that are almost exclusively emitted by plants. In the boreal region, VOCs – especially monoterpenes – can have major contribution to the radiative forcing and therefore also to the regional climate (Paasonen et al., 2013).

3.3.1 VOC Measurements

VOC measurements are generally complex due to the amount of measured molecules and their low concentrations. During last two decades, a mass spectrometry has become more and more popular whereas a gas chromatography is a more traditional technique. Unfortunately, laser spectrometers – that are widely used for flux measurements of some other trace gases, such as CH_4, COS and N_2O – are not available for most biogenic VOCs, such as monoterpenes. Isoprene flux measurements can be obtained with a fast isoprene analyzer (FIS) but the technique is not applicable for other VOCs (Rinne et al. 2016).

In the boreal region, the VOC concentration are typically very low and the used instrument should be as sensitive as possible (detection limit < 10 ppt). If the target is to measure VOC fluxes, the requirements are even stricter. In warmer climate and/or different ecosystem (Misztal et al. 2011; Kaser et al. 2013; Schallhart et al. 2016), the technical requirements are not necessary as demanding. However, this is very subjective thing. The more sensitive the instrument is, the more compounds it can detect. For example, the isoprene flux above an oak forest can be relatively large but the monoterpene flux is still as small as in Hyytiälä above a boreal forest (e.g. Park et al. 2013; Schallhart et al. 2016). In addition, more sensitive instrument makes also post-processing (e.g. different flux corrections, see Mammarella et al., 2017) easier and more reliable due to higher signal-to-noise ratio.

3.3.2 Instruments

Ionicon is currently the most well known manufacturer what comes to the mass spectrometers. Tofwerk/Aerodyne collaboration and Kore Technology sell also a similar type of VOC detectors. All these companies provide time-of-flight mass spectrometers with proton transfer reaction ionization technique. In addition, Syft Technologies (Selected Ion Flow Tube Mass Spectrometry) have developed their own quadrupole mass spectrometer for VOCs. Generally, time-of-flight mass spectrometry is the preferred technique because it is also capable of performing conventional EC flux measurements (Müller et al., 2010).

Gas-chromatographies (GC) are manufactured by – for example – Agilent and Thermo Fisher Scientific. GCs have usually a quite long sampling period (e.g. 30 min) and they are not suitable for the direct VOC flux measurements with the EC. Instead of that, a gradient technique is a reliable flux measurement method also for these instruments (Rinne et al., 2000).

The cheapest instrument from Ionicon – PTRTOF 1000 (https://www.ionicon.com/product/ptr-ms/ptr-tofms-series/ptr-tof-1000) – costs around 250 000 EUR and is capable of doing flux- and concentration measurements in various locations.

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3.4 Clouds, cloud condensation nuclei and precipitation

Forests play a crucial role in mitigating climate change. In addition to substituting fossil fuel use (bioenergy, carbon intensive materials), the forests act as a significant carbon sink and a source of climate cooling aerosol particles. At the same time, an enhanced forest cover decreases surface albedo and can have a warming potential while the aerosol effect on clouds is cooling. We have recently shown with comprehensive observational data from SMEAR II station in Southern Finland that the boreal forests act as a source for volatile organic compounds (VOCs), aerosol particles and cloud condensation nuclei, cloud droplets and enhance the specific water content and water liquid content of clouds through evapotranspiration (Figs 3.2 and 3.3).

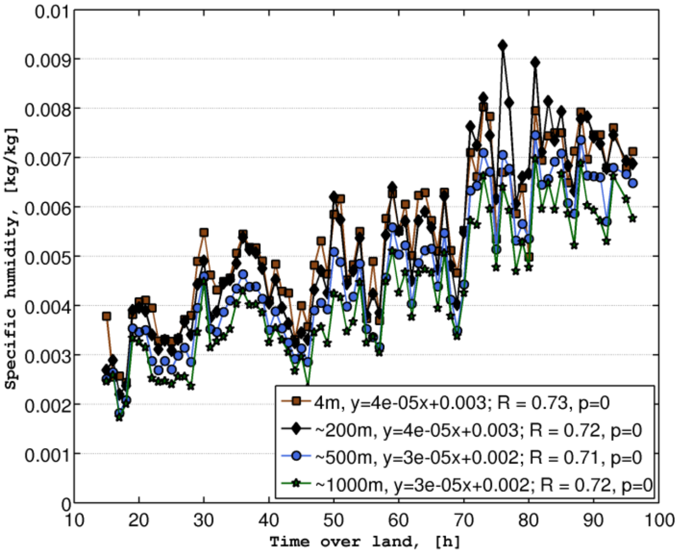

Figure 3.2a**.** Specific humidity as a function of time-over-land in the surface layer.

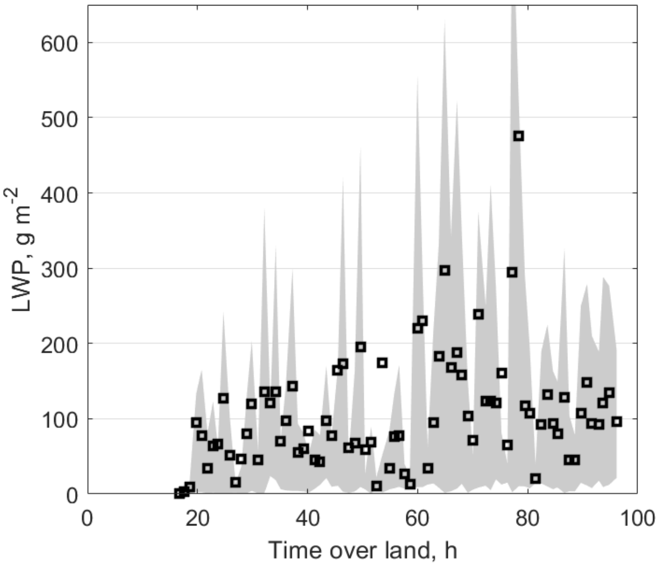

Figure 3.2b**.** Liquid Water Path (LWP) as a function of time over land. As the air mass is transported over the boreal forest, water accumulates until 75h. Further decline is due to precipitation. Squares – mean values in 1 h bins of time over land. Grey shade shows 20 and 80 percentiles of data in the bins.

Furthermore here we present here the first estimations, how big a forest is needed to dominate the aerosol-cloud-precipitation interactions and produce self-sustaining cloud and precipitation system in the forest environment. Based on the data (Kulmala et al., 2019) from the boreal coniferous forest-dominated site, we estimate the forest size to be 1 000 000 km^2. Such forested area will have carbon sequestration rate (carbon sink) of 1/50 of the global annual carbon emissions. This can be utilized, when considering regional scale afforestation and reforestation activities in semi-arid and beyond regions that are significant and crucial tool to mitigate climate change through biosphere carbon sequestration and storage in a sustainable manner. Such actions could give humankind more time to significantly reduce carbon emissions and further to control the carbon balance of the atmosphere – earth surface continuum.

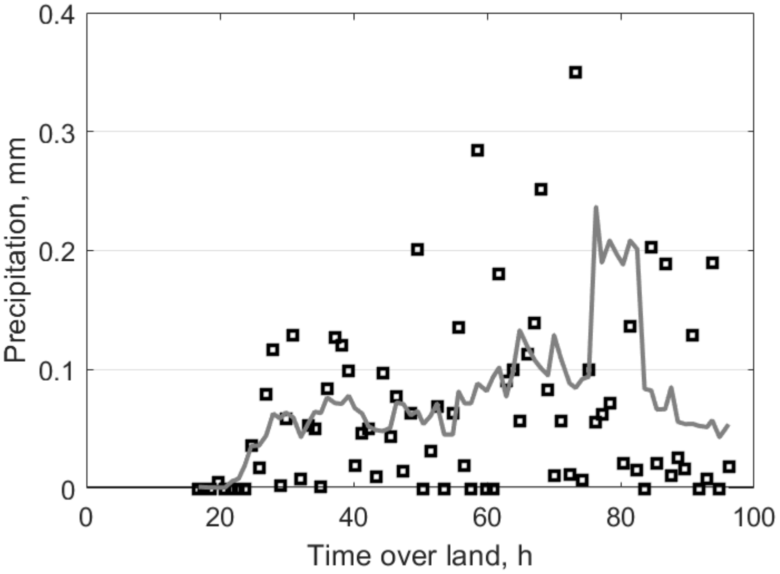

Figure 3.3 Accumulated precipitation in a grid-box around Hyytiälä as a function of time-over-land. Precipitation accumulated during 1 h. Squares – mean values in 1 h bins of time over land. Curve – running average of the data shown by squares over 5 neignbouring points. There is an outlier at (78 h; 1 mm) not shown in the figure, corresponding to heavy rain.

Overall, the aerosol-cloud processes actually make the forest even more effective in mitigation of climate change than in the case of carbon sink only. Kulmala et al. (2004) suggested a negative climate feedback mechanism whereby higher temperatures and CO_2-levels boost continental biomass production, leading to increased biogenic secondary organic aerosol (BSOA) and CCN concentrations, tending to cause cooling. The consolidated process-level understanding together with scientific synthesis of the feedbacks facilitates breakthroughs in supporting the resilience of ecosystems to environmental stresses caused by the climate change. These CarbonSink+ analysis will provide tools 1) to optimize afforestation and reforestation activities e.g. in semi-arid and other dry environments, and 2) to increase the carbon uptake of terrestrial ecosystems to tackle anthropogenic emissions of greenhouse gases and consequent warming. The first quantitative analysis was performed by Kulmala et al. (2014). The CarbonSink+ includes the continental biosphere-atmosphere-cloud-climate (COBACC) feedback loop from carbon sink to aerosol source, and aerosol-cloud-precipitation feedbacks. For the complete analysis also forest vs no-forest surface albedo investigations are needed.

The frequent new particle formation events and subsequent growth to CCN sizes are observed all around the world in boreal or temperate forests and savannah (Kulmala et al. 2004, Kerminen et al. 2018). In order to analyze the net effect of the biosphere emissions to aerosol and cloud properties, we utilize air mass back-trajectories and estimate, how long time the air mass has spent over the boreal environment. This is called time-over-land, similar to Tunved et al. (2006), who showed that the time over land is a crucial factor to determine, how the particles are able to grow to CCN sizes and beyond. Recently, we have extended the analysis and analyzed aerosol size distributions, aerosol mass, mass of low and semi-volatile organic aerosols, in-situ measured CCN concentrations, backscattering observed both in-situ and ground-based remote sensing (which actually agreed nicely with each other), liquid water path and cloud droplet concentrations (Petäjä et al., 2019). All of those increase as a function of time-over-land and have a clear maximum at 70-80 hours (see Petäjä et al., 2019). In some cases, after 70-80 hours the observed variable could also be rather constant.

The NPF is typical when the air mass is coming from the North Sea / the Arctic Ocean. The direct distance from SMEAR II station (Hyytiälä) to North Sea is around 800 km. The time over land analysis made by Tunved et al. (2006) as well as our present analysis show that the typical time to produce CCN, cloud droplets and precipitation is 70-80 h. The corresponding distance above land is 800 km. Anyhow, the time over the land analysis takes this into account and we can confidentially say that taking into account the clean sector the distance is 800-1000 km from the sea (Kulmala et al., 2019). Therefore, the conservative estimate to obtain precipitation is 1000 km distance corresponding ca 1 000 000 km^2 area (Kulmala et al., 2019. However also 800 x 800 km = 0.64 Mkm^2 could be enough.

The bigger the forest the higher the water flux from the ecosystem is. Furthermore the bigger forest produces larger amount of aerosol particles. At certain level of cloud liquid water content the more aerosol particle the more cloud droplets we have, and the smaller cloud droplets are. This will enhance cloud life time and increase cloud albedo. However, when there is enough cloud water the clouds will precipitate, and this is what we have seen.

On the other hand, 1 000 000 km^2 area of typical forest will have carbon sequestration of the same magnitude than the annual global carbon emissions within 50 years in boreal environment. In the case of subtropical dry the value is 6.7e15g and for Boreal conifer 4.8e15g (Pan et al 2013).

Forests store carbon in aboveground biomass and soil (belowground biomass and soil organic matter, composed of e.g. decomposing plant material and microbes), yielding net primary productivity (NPP). The aboveground biomass gain can be harvested and used for production of energy and other materials to avoid CO_2 emissions. However, in many ecosystems the soil organic pools are many times larger carbon storage and can provide significant additional climate benefit. To obtain proper knowledge on the amount of carbon stored in the soil, further investigations on soil organic carbon stocks (SOC) are needed.

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3.5 Feedback loops and their observations in boreal forests

3.5.1 Background

Terrestrial carbon sinks have recently raised general interest, with forests playing an important role in this respect (Pan et al, 2011, Grassi et al., 2017) as the present rates of atmospheric CO_2 growth can not be explained without a substantial increase in terrestrial carbon sinks (Sarmiento et al., 2010, O'Sullivan et al., 2016). Boreal forests play a relevant role for the carbon balance of the planet being an essential carbon sink. Understanding the mechanisms regulating carbon exchange in the boreal forest ecosystems is therefore of crucial importance. Uncertainties in the carbon cycle in existing climate models substantially alter climate predictions (Friedlingstein et al., 2014). Besides rather obvious effect of changing green mass, although e.g. forest management effects are not included in all earth system models, on the ecosystem's CO_2 balance, chains of complex interactions between the ecosystem and atmosphere can be identified (Kulmala et al., 2013). Here we describe two carbon-based continental biosphere-atmosphere-cloud-climate (COBACC) feedback loops in boreal forests (temperature-related and GPP-related) and our current understanding on the physical processes behind these loops.

Schematics of the loops are shown in Fig. 3.4. CO_2 increase may cause an increase in the gross primary production (GPP) of an ecosystem, the effect known as CO_2 fertilization (CO_2 – GPP link in Fig. 3.4). GPP quantifies the carbon dioxide flux towards the ecosystem, thus characterizing the ecosystem photosynthetic activity. Photosynthesis is responsible for carbon supply to the plants, necessary for their normal function. Some plants species have special carbon storages to allocate part of the carbon received in the process of photosynthesis. Plants can use this stored carbon, as well as the carbon from *de novo* photosynthesis, to produce biogenic volatile organic compounds (BVOC) (Ghirardo et al., 2010). Enhanced photosynthesis may therefore lead to an increase in BVOC emissions (GPP – BVOC link in Fig. 3.4).

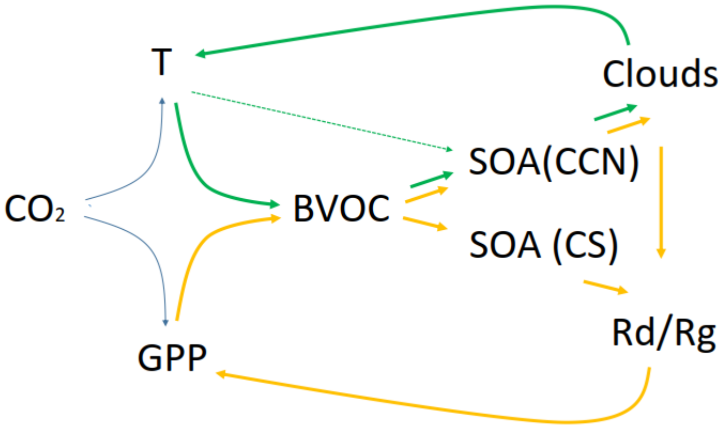


Figure 3.4 Schematic of the continental biosphere-atmosphere-cloud-climate (COBACC) feedback loops. Temperature-related feedback loop is shown in green color, GPP-related feedback loop - in orange color. CO2 – concentration of carbon dioxide, GPP – gross primary production, BVOC – biogenic volatile organic compounds, SOA – secondary organic aerosol, CS – condensation sink, CCN – cloud condensation nuclei, Rd/Rg – fraction of diffuse radiation in global radiation, T – temperature. See the detailed description of the loops in the text.

In addition, an increase in CO_2 concentration in the atmosphere leads to the temperature increase due to the greenhouse effect (CO_2 – T link in Fig. 3.4). Temperature increase boosts emissions of many BVOCs (mono- and sesquiterpenes) through the mechanisms similar to evaporation (Grote et al., 2013). The growing exponential dependence of BVOC emissions on temperature is observed for the emissions using carbon from the storage pool (Tingey et al., 1980). The emissions processing carbon from de novo photosynthesis (e.g. isoprene) decreases after some threshold value of temperature because high temperatures destroy the photosynthetic apparatus of plants (Monson et al., 1992). However, these values of temperature (40°C) have so far been almost never observed at the middle and high latitudes; therefore, all emissions in boreal forests generally grow with temperature (T-BVOC link in Fig.3.4). Climate change induced heat spells may have some effect on BVOC production in mid latitudes in the future. However, in ever-green trees growing in dry region of tropics, like pines and eucalypts, the monoterpene emissions are not only related to daily conditions but also on the stored VOCs in long-term.

Note that both temperature-related and GPP-related loops share BVOC-aerosol link. BVOCs are oxidized in the atmosphere to form low-volatile organic vapours (Hallquist et al., 2009). The vapours contribute to the processes of new particle formation and growth (Ehn, 2014), which have two important consequences. One is an increase in the number of particles able to act as cloud condensation nuclei (BVOC-CCN link in Fig. 3.4), and another is an increase in the condensation sink (BVOC – CS link in Fig. 3.4). Condensation sink (CS) is a parameter proportional to aerosol surface area and mainly sensitive to aerosol particles' increase in size (Lehtinen et al., 2004, Ezhova et al., 2018). The link between BVOC and secondary organic aerosol (SOA) was investigated using different approaches. Particles inside one air mass moving over land are constantly growing because organic vapours produced from BVOCs emitted by forests condense onto aerosol particles. The increase in total aerosol mass with time over land has been demonstrated by Tunved et al. (2006) and Liao et al. (2014). With this approach, the authors were able to show that aerosol growth is a process essentially non-local in space and time. However, the applicability of this method is limited at the continental sites. Besides, while aerosol characteristics are measured, the monoterpenes' emissions are parameterized by Tunved et al. (2006) and Liao et al. (2014). Kulmala et al. (2014) proposed a different approach to study BVOC-SOA link, based on in-situ atmospheric observations. The authors considered CS to be a function of the particles' growth rate (GR), calculated from the particle number-size distribution. The GR is larger for higher concentrations of BVOCs and organic vapours, and CS was observed to increase with GR. This approach considers BVOC-related processes indirectly, as growth rate as a parameter obtained from aerosol measurements and it accounts for all the condensing vapours present in the atmosphere. However, this approach reduces the data set to only NPF days, which can be relatively rare in summer (Dada et al, 2017). One more approach accounting for BVOCs effect indirectly is linking temperature to aerosols. The increase in CCN with temperature has been demonstrated by Paasonen et al. (2013) based on atmospheric observations from eleven sites in different parts of the world. While evidence for BVOC-SOA link in general has been obtained, the role of particular BVOCs and organic vapours for the processes of new particle formation and growth based on the observations in boreal forest remains largely an open question.

The next step of the temperature-based feedback loop is from CCN to clouds (Fig. 3.4). The effect of aerosols on cloud cover is not well established and is itself a subject for various feedbacks. However, the first indirect effect (Twomey, 1977) has been confirmed by many studies (Rosenfeld, 2014). Cloud reflective properties strengthen when the number of cloud droplets increases at the constant liquid water content (Twomey, 1977). Therefore, increase in CCN leads to an increase in clouds' albedo (reflection of solar radiation), resulting in cooling of the atmosphere (clouds-T link in Fig. 3.4). Thus, the temperature-related COBACC feedback loop (shown in green color in Fig. 3.4) prescribes a negative feedback on temperature.

The GPP-related loop (shown in orange color in Fig. 3.4) includes two effects on solar radiation due to secondary organic aerosol, namely particles acting as CCN and increasing aerosol loading (CS). CS-related link corresponds to the 'clear-sky' part of the GPP-related loop, whereas CCN-related link corresponds to the 'cloudy' part. In what follows we focus mainly on photosynthetically active radiation (PAR) which corresponds to the range of wavelengths between 400 and 700 nm in the solar radiation spectrum. Incoming PAR consists of direct and diffuse radiation. Direct radiation comes from the direction of the sun whereas diffuse radiation comes from all other directions. Increase in aerosol loading under clear sky, as well as clouds present in the sky, lead to an increase in the diffuse fraction of solar radiation due to scattering (SOA-Rd/Rg links in Fig. 3.4). Under clear sky and at the low aerosol loading, PAR is mainly direct. In this case, only tops of the canopies of forest ecosystems can get enough light for effective photosynthesis. At the same time, well-pronounced shadows appear inside the canopy decreasing light availability and reducing photosynthetic activity of the whole forest ecosystem. When the diffuse fraction of radiation increases, more incoming radiation arrives from different angles. As a result, more light photons penetrate inside the canopy and can be captured and used for photosynthesis (Gu et al., 2002, Niyogi et al., 2004). This leads to an increase in light use efficiency (LUE) - a parameter, quantifying amount of carbon dioxide fixed by an ecosystem per unit absorbed PAR. At the same time, increase in the diffuse fraction of radiation is the consequence of the increase in scattering and reflecting agents (aerosol and clouds) in the atmosphere. Therefore, total incoming radiation reaching the surface decreases when the diffuse fraction of solar radiation increases. A significant increase in diffuse radiation usually leads to decrease in GPP, because total radiation decrease can be strong and light becomes a limiting factor for photosynthesis. However, a moderate increase in diffuse radiation due to aerosol and some types of clouds may lead to an increase in ecosystem GPP (Rd/Rg – GPP link), due to the effect of diffuse radiation fertilization (DRF).

At remote sites in boreal and hemiboreal forests, on clear days, aerosol (CS) can lead to the increase in the diffuse fraction of solar radiation from 10%, corresponding to clean atmosphere, to ~ 27% characteristic of relatively high aerosol loading (Ezhova et al., 2018). The corresponding DRF effect estimated from observations is 6-14% increase in GPP. Maximum increase, up to 10-30% for different ecosystems as compared to clean atmosphere and clear sky conditions, is associated with some particular types of clouds. At the same time, optically thick clouds reduce GPP of an ecosystem. Therefore, the 'clear sky' or CS-related part of the feedback loop results in the positive feedback for GPP, while the 'cloudy sky' or CCN-associated effect for GPP may be either negative or positive.

3.5.2 GPP-based, 'clear-sky' part of the feedback loop: estimates and instrumentation

The focus of the present project is on the quantification of the carbon-induced terrestrial feedback loop based on field observations. The feedback loop (constituting part of the loop in Fig. 3.4) is illustrated in Fig. 3.5 and the main idea under this loop can be formulated as follows (Kulmala et al., 2014). The increase in the CO_2 concentration stimulates photosynthesis and, consequently, leads to an increase in GPP. More active plants produce more BVOC, a source/precursors of low-volatile vapours responsible for the formation and growth of atmospheric aerosol particles. Subsequently, there are more secondary organic aerosol (SOA) able to scatter solar irradiance increasing the diffuse fraction of solar irradiance. The latter, in its turn, enhances the plant LUE. This may lead to an increase in GPP and a larger CO_2 uptake, so CO_2 can be removed from the atmosphere more effectively. The aim of the project is to understand how significant this effect can be and how can it be taken into account in the commercial carbon sinks or is it too complicated and expensive to measure.

Currently, only one station in Eurasia (SMEAR II, Finland) provides the data set needed to quantify the whole feedback loop (Fig. 3.6). Four stations in Finland, Estonia and Russia have enough data to quantify at most two steps of the loop. All these stations lack BVOC measurements, some also lack diffuse radiation or aerosol measurements.

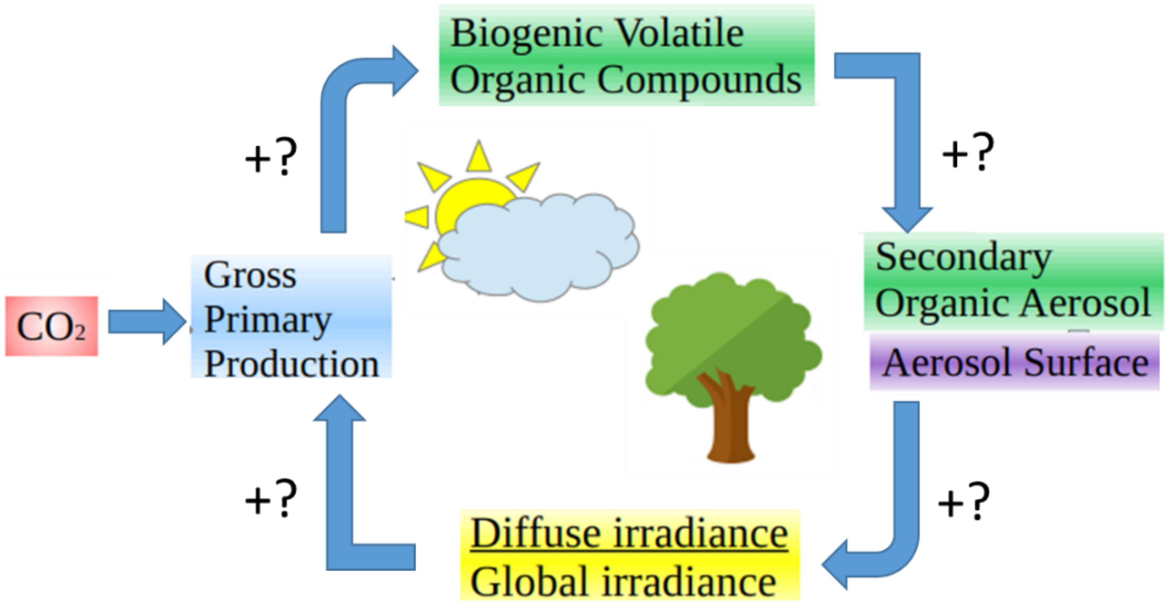
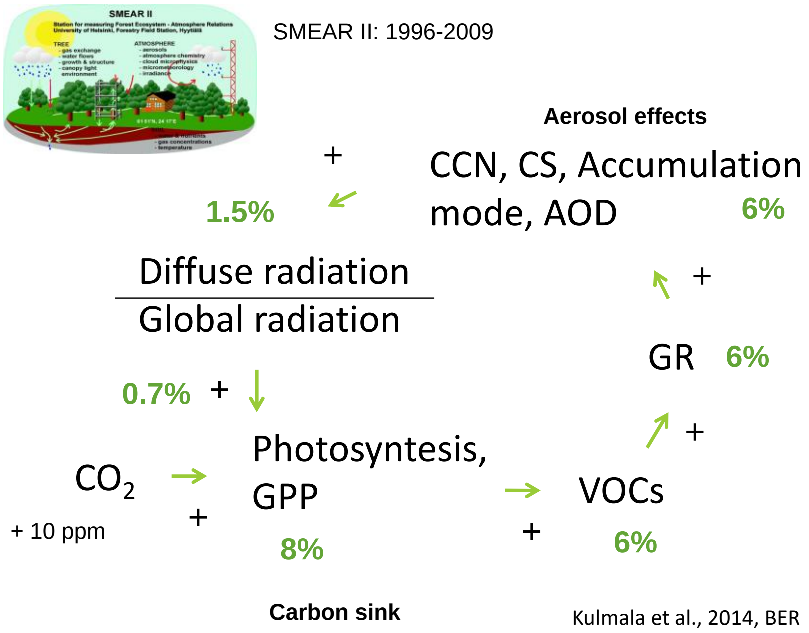


Figure 3.5 Continental Atmosphere-Biosphere-Climate-Cloud feedback loop (GPP-based, clear sky conditions).

Instruments that are needed for quantification of the feedback loop:

1) BVOC measurements: PTR-MS (Proton Transfer Reaction Mass Spectrometer) or GC-MS (Gas Chromatography Mass Spectrometer) – ca 450 000 Euro;
2) SOA measurements: DMPS+CPC (Differential Mobility Particle Sizer and Condensation Particle Counter) – ca 95 000 Euro;
3) Radiation measurements: diffuse and global radiation sensors – ca 5 000 Euro;
4) Photosynthesis measurements: micrometeorological set of instruments (CO2 fast response concentration measuring device + 3D anemometer) – ca 30 000 Euro.

If this is a new station, then standard meteorological measurements should be added (Väisälä station – ca. 50 000 Euro); it is likely that the effect of clouds needs to be considered, therefore ceilometer can be added to this set (can be included into Väisälä package).



Kulmala et al., 2014, BER

Figure 3.6 First calculations based on the feedback loop observed in Hyytiälä. Values: Increase of atmospheric concentration is + 10 ppm, if this is ca 50% of emissions i.e. that emissions are + 20 ppm. Terrestial carbon sink (25% of emissions) ca. 5 ppm.

If there is a positive feedback in the system (the system can be considered as a nonlinear amplifier with a positive feedback):

1) The amplifying coefficient K = 1.08 due to CO_2 fertilization effect from the scheme in Fig. 3.4 (if we assume that the effect of feedback is not there yet).

2) Then also, 0.07GPP continuously comes to the input of the system during clear sky time time due to the positive feedback from diffuse radiation fertilization (DRF).

3) The resulting amplification coefficient will be: $K_1 = GPP_{out}/GPP_{in} = K/(1-0.007K) = 1.08/(1-0.007*1.08) = 1.088$ due to the feedback. The increase in carbon uptake due to diffuse radiation would be 8.8% instead of 8%, so 0.44 ppm instead of 0.4, if 5 ppm is assumed to be a total carbon sink. Clear time constitutes on average 12% of all time at SMEAR II, then: 0.44*0.12 + 0.4*0.88 = 0.405 ppm increase.

Max 6% increase in GPP due to aerosol-associated DRF at SMEAR II: $K_1 = GPP_{out}/GPP_{in} = K/(1-0.06K) = 1.08/(1-0.06*1.08) = 1.154$. The associated increase in the carbon sink is 0.77 ppm. Clear time constitutes on average 12% of all time at SMEAR II: 0.77*0.12 +0.4*0.88= 0.44 ppm increase.

However, ca 50% of time we have clear sky or clouds favouring GPP increase (12% clear sky and ca 40% Cumulus and Altostratus/Altocumulus clouds). Clouds DRF effect on GPP is more than 0.7%.

One can expect max 11% increase in GPP in Hyytiala due to clouds, on average 6% for estimates. The amplification coefficient due to clouds: $K_1 = GPP_{out}/GPP_{in} = K/(1-0.06K) = 1.08/(1-0.05*1.08) = 1.154$. It would give ca 0.77 ppm increase for 5 ppm total sink. For 50% of cloudy time favouring GPP increase due to DRF feedback, the resulting estimate would be 0.77*0.5 +0.4*0.5= 0.585 ppm increase instead of 0.4 ppm without feedback effect. .

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4. How to strengthen ecosystem carbon sinks?

Tuomo Kalliokoski

The Paris Agreement includes strategic Nationally Determined Contributions (NDCs) which main aim is strive development of pathways toward low net GHG emissions. Almost 70% of nations indicated in their NDCs they will use the land sink to reach their mitigation targets. Also in IPCC sr1.5 (IPCC 2018) virtually all integrated assessment model (IAM) scenarios that limit either peak or end-of-century warming to 1.5°C use land-intensive carbon dioxide removal (CDR) technologies (see Cross-Chapter Box 7 in IPCC sr1.5 and references therein). Thus, following the climate objective of Paris Agreement and the pathways outlined in IPCC sr1.5 the role of ecosystem carbon sinks in the mitigation of climate change has been further emphasized. There are international programs for improving state of forests especially in tropics (e.g Reducing Emissions from Deforestation and forest Degradation in developing countries, REDD+). Also the potential role of land-focused negative emission technologies is studied and explored actively (e.g., large-scale afforestation, bioenergy combined with carbon capture and storage BECCS, biochar formation, soil carbon sequestration). All these approaches include large uncertainties and therefore mitigation by land use sector needs to be done on a sound scientific basis (Keenan & Wiliams 2018).

The roadmap for rapid decarbonization (Rockström et al. 2017) estimated the potential of stopping deforestation and afforestation to be 0,5 – 3,6 GtCO2eq year^{-1} (Fig. 4.1, 'Land use sector'). In their analysis, the remarkable amount of negative emissions by BECCS were needed in addition to the changes in land use sector. Also most of the IPCC sr1.5 scenarios include high deployment of BECCS, the highest estimates of bioenergy produced through BECCS globally being over 400 EJ year^{-1}. However, there is wide consensus that sustainable limit for bioenergy is somewhere around 100 EJ year^{-1} (current production around 50 EJ year^{-1}, Creutzig et al. 2015, see also chapter 5 in IPCC sr1.5).

Global vegetation currently stores around 450 Gt of carbon. In the hypothetical absence of land use, potential vegetation would store around 916 Gt of carbon, under current climate conditions. Deforestation and other land use changes explains up to 58% of the difference between current and potential (Erb et al. 2018). Mitigation potentials are concentrated in tropical regions and dominated by reduced rates of deforestation and reforestation (Houghton 2013, Canadell and Schulze 2014, Grace et al. 2014, Houghton et al. 2015, Griscom et al. 2017). However, according to the analysis of Erb et al. (2018) over 40% of the difference is not due to land use changes but due to intensive land use, e.g. forest management. The large difference between current situation and potential emphasizes the mitigation potential of land use sector, especially forests.

Potential storage of global vegetation could never be reached but in the specific study (Griscom et al. 2017) considering land area restrictions due to food, fibers and other production, infrastructure and biodiversity etc., the estimate of land use sector total mitigation potential was 23,8 GtCO2eq year^{-1} net emission reductions through 2030. The study presents versatile mitigation measures labeled as "Natural Climate Solutions" (NCS) for strengthening ecosystem carbon sinks (Fig. 4.2). This value, however, does not include economic constrains. This estimate is ≥30% higher than estimates from some earlier studies (see Table 1, in Cross-Chapter Box 7 of IPCC sr1.5). For example, Smith et al. (2013) estimated the lower end of the mitigation potential of land-use sector to be only 3 GtCO2eq year^{-1}. The higher end was, however, 19.9 GtCO2eq year^{-1} when both supply- and demand-side measure were accounted for.

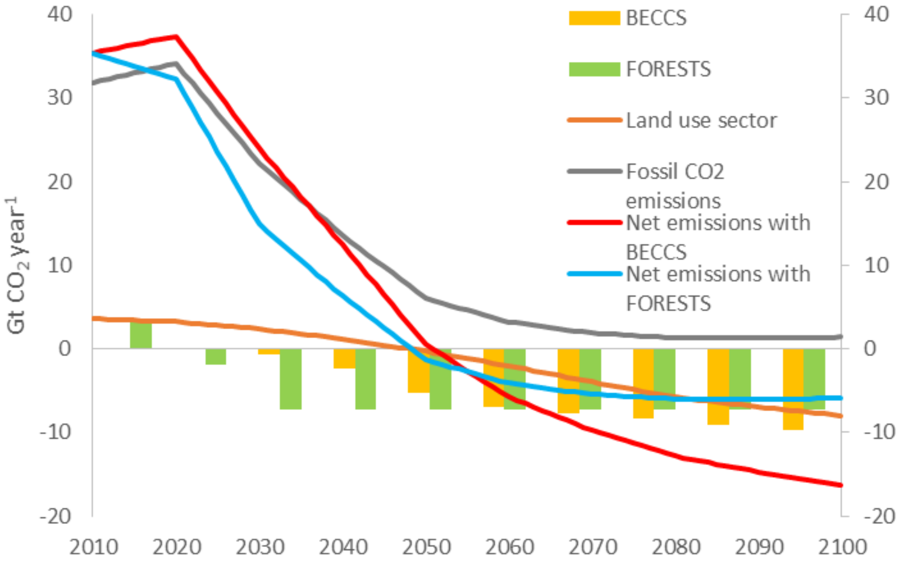

Figure 4.1 We need to halve fossil emissions every decade and transform land use sector from source to notable sink for keeping global warming under 2°C during this century. In addition for those actions, we need negative emissions (“BECCS” in figure) or considerable strengthening of ecosystem carbon sinks (“FORESTS” in figure). Land use sector, fossil emissions and BECCS are based on Rockström et al. (2017). In the net emissions with FORESTS curve, the mitigation level reached on 2030 by actions in forests (Griscom et al. 2017) is projected to be stable during whole century.

Griscom et al. found possible to reach about half of this total mitigation potential (i.e. 11.3 GtCO2eq year^{-1}) cost-effectively (<100 USD MgCO2e^{-1} y^{-1}). Half of this cost-effective mitigation was reached due to increased carbon sinks by different actions, while other half of the mitigation was obtained by the pathways avoiding further emissions of GHGs. These cost-effective NCS’ provide 37% of the necessary CO2eq mitigation between now and 2030 and 20% between now and 2050. The NCS could be seen as partly substituting the enormous deployment of BECCS (Fig. 4.1).

Most NCS pathways can maintain the 2030 the reported mitigation levels for more than 50 years. Thereafter, the proportion of mitigation provided by NCS further declines as the proportion of necessary avoided fossil fuel emissions increases and as some NCS pathways saturate. Higher estimate by Griscom et al. than found in earlier studies is partly explained by including more mitigation options from wetlands and agriculture than included by others, partly due to larger mitigation in temperate and boreal ecosystems. The activities targeted for increasing forest carbon storages offer over two thirds of cost-effective NCS mitigation needed to hold warming to below 2 °C, yielding 7,32 GtCO2eq year^{-1} (Griscom et al. 2017, “FORESTS” in Fig. 4.1). The actions in the forests include e.g. reforestation, avoided forest conversion, improved plantations, fire management and natural management of forests (Table 4.1). This level was reached when cost efficiency was accounted for. However, the maximum mitigation potential of forest based measures was estimated up to 16,2 GtCO2eq year^{-1}. Thus, the actual potential depends on the development in the other sectors and the relative cost-efficiency of the actions in the forest sector. The NCS improve also other land based ecosystem services like biodiversity, water filtration, flood control, and soil quality. Due to these synergistic effects the cost-effective implementation of NCS could be higher than in the analysis of Griscom et al (2017).

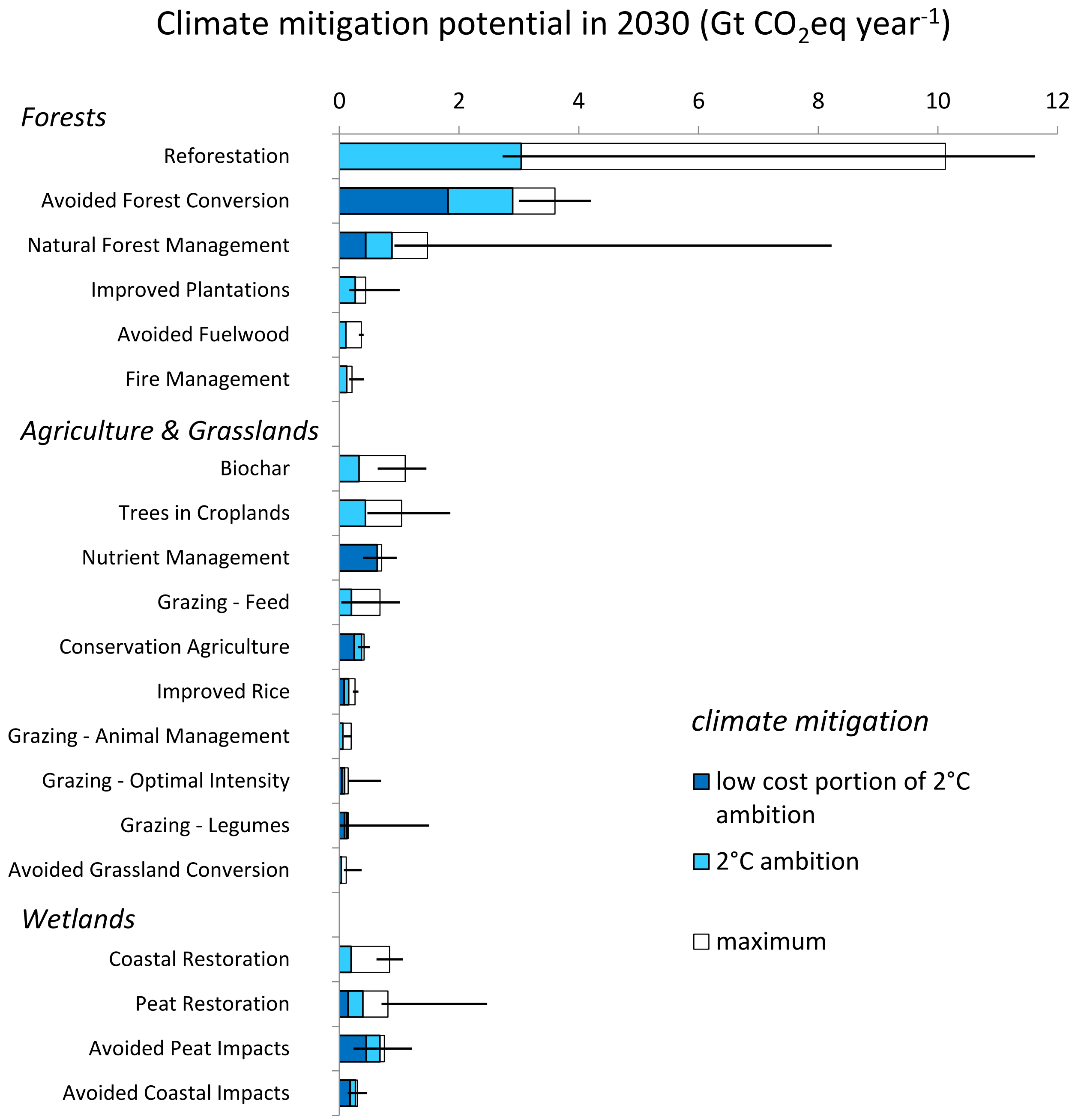

Figure 4.2 Different ecosystem related mitigation pathways at the year 2030 labeled as Natural Climate Solutions in the study of Griscom et al. (2017). Light blue = cost-effective mitigation levels when global warming <2 °C (<100 USD MgCO2e^{-1} y^{-1}). Dark blue = portion of low cost (<10 USD MgCO2e^{-1} y^{-1}) when global warming <2 °C. The error bars are 95% confidence intervals. Improved forest management (both forest management changes and improved plantations) offers large and cost-effective mitigation opportunities, many of which could be implemented rapidly without changes in land use or tenure.

Table 4.1 Estimated mitigation potential of different actions related to forests (Griscom et al. 2017). Values are the flux at year 2030. Different actions have different time span until they saturate, e.g. in temperate vegetation zone the effect of reforestation saturates > 30 years, whereas avoided forest conversion effect saturates only after 100 years. Max mitigation = no cost costrain, Cost effective = marginal abatement mitigation cost not greater than ∼100 USD $MgCO2^{-1}$ as of 2030, Low cost = <10 $USDMgCO2^{-1}$.

	Gt CO2eq $year^{-1}$		
Action	Max Mitigation	Cost effective	Low Cost
Avoided forest conversion	3,603	2,897	1,816
Reforestation	10,124	3,037	0
Natural Forest Management	1,470	0,882	0,441
Improved Plantations	0,443	0,266	0
Fire Management	0,212	0,127	0
Avoided Woodfuel Harvest	0,367	0,110	0
Total	16,219	7,319	2,257

For Finland, the study of Griscom et al. (2017) gives a maximum mitigation potential of NCS to be 54,2 Mt CO2eq $year^{-1}$ at 2030. Changes in forest management practices by increasing forest rotation length and having milder thinnings the forest sink could be increased by 13,71 Mt CO2eq $year^{-1}$. The study gives very high potential for peatlands where restoration of ditched peatlands could decrease emissions by 34,32 Mt CO2eq $year^{-1}$ and avoided emissions from peatlands up to 8.35 Mt CO2eq $year^{-1}$. Other actions, like reforestation 1,69 Mt CO2eq $year^{-1}$, are less important but not totally marginal. All these region specific values are very uncertain and should be considered as realizations of specific study with given assumptions. However, the mean age of Finnish forests is around 50 yrs and there are many studies showing that Finland has good potential for increasing forest carbon storage during next 30-50 years due to young and well growing forests (Sievänen et al. 2015, Kallio et al. 2013, Heinonen et al. 2017). On the other hand, gaining climate change mitigation by the increased use of forest biomass seem to be challenging mainly due to difficulties to obtain high enough displacement of fossil fuels (Soimakallio et al. 2016). In Finnish case, model analyses have shown that forest carbon sink may reduce up to two tons of CO2 per harvested m3 during next decades (Sievänen et al. 2014, Lehtonen et al. 2016).

The persistence of the carbon stored in the ecosystems in the mitigation projects is well-known challenge. How to suppress abiotic (e.g. storms) and biotic damages (insects, pathogens etc.) in large regions needs specific attention in the ecosystem based mitigation projects. Climate change induced adverse effects could reverse terrestrial carbon sinks by midcentury and erode the long-term climate benefits of NCS (Keenan & Williams 2018). Also aspect to keep in mind is that reducing rates of deforestation constrains the land available for agriculture and grazing, with tradeoffs between diets, higher yields and food prices (Chapter 4 in IPCC sr1.5, Erb et al. 2016, Kreidenweis et al. 2016). This raises a concern of cross-biome leakage (Popp et al. 2014a, Strassburg et al, 2014, Jayachandran et al. 2017) and encroachment on other ecosystems (Veldman et al. 2015).

Also the importance of old forests increases along the efforts to increase the long-term storage of carbon in ecosystems. The carbon dynamics in the old forests are not well known although common belief of old forests being carbon sources is not valid in the light of current scientific understanding (Zhoul et al. 2006, Luyssaert et al. 2008, Schulze et al. 2012, Clemmensen et al. 2016). Focused measurements both in pristine Northern boreal forests and in tropical forests are in demand if long-term success of these mitigation projects are wanted to ensure.

There is urgent need for aggressive, simultaneous implementation of mitigation from both NCS and fossil fuel emissions reductions. Emerging regional assessments offer new perspectives for upscaling. Strengthening coordination, additional funding sources, and access and disbursement points increase the potential of e.g. REDD+ and other frameworks in working towards 2°C and 1.5°C limits (Well and Carrapatoso, 2017).However, the only sustainable way in the long-term to obtain mitigation through NCS and land use intensification is to implement them in locally appropriate ways with best practices that maximize resilience (IPCC sr1.5, Chapter 5).

Initiatives for further reading

The New York Declaration on Forests, https://nydfglobalplatform.org/

The Bonn Challenge, http://www.bonnchallenge.org/content/challenge

World Business Council on Sustainable Development Vision 2050,
https://www.wbcsd.org/contentwbc/download/1746/21728

The “4 pour 1000” initiative, https://www.4p1000.org/

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5. Conceptualised measurement scheme and costs

Sami Haapanala, Tuomo Kalliokoski, Markku Kulmala

A new carbon market system should consider all factors affecting climate. In addition to the carbon balance, necessary factors include balance of other greenhouse gases, surface albedo, and other feedback mechanisms, such as CarbonSink+. In this chapter we define a cost effective, i.e. as simple as possible but accurate enough, measurement scheme to verify climate effects of forest. The methodology is planned for commercial applications, rather than for scientific purposes. In 5.1 we describe the method and required measurements. In 5.2 we estimate the amount of required manpower and prices of the equipment.

For a successful carbon market system, objective criteria for site selection should be defined. Items to consider when selecting an area having good potential for commercial carbon sink include at least: Ownership of the area, terrain and soil properties, current status of the ecosystem and potential for increasing stored carbon in a sustainable way, and infrastructure.

5.1 Method description

Figure 5.1 describe a scalable scheme for creating and verifying climate friendly forest. Details for measuring the initial state of and monitoring afforestation/reforestation site are presented separately on Figs 5.2 and 5.3.

5.1.1 Planning phase

The upper part of the scheme (Fig. 5.1) show the planning phase of the project. For the design of a monitoring system applied as part of an afforestation project (e.g. for the carbon credit market) many factors need to be considered, such as the total costs, desired level of accuracy and, with it, its reliability.

Step 1: The project should begin with a careful description of the current status of the ecosystem, and external factors affecting it (Management history, Climate data).

Step 2: Initial vegetation and carbon inventory (Fig. 5.2) consists of the same elements as monitoring by manual inventory methods. The main parts are forest biomass and soil carbon measurements which must be conducted in dense enough grid, or other systematic manner e.g. circular sample plots. The grid resolution or number of the sample plots depends on the vegetation type and needed accuracy.

Step 3: Management and Monitoring plans (Fig. 5.3).

> ***Management plan:*** Description of the actions which will take place for fulfilling the objectives of the mitigation project. The Plan has to include the time span (e.g. for next 10 years) and description of planned forest management operations like tending of saplings, thinnings, damage preventions etc. All these have to be given specific timing in the plan. These management actions should be related with monitoring plan in order to catch changes due to operations.
>
> ***Monitoring plan:*** Apart from the number of afforested areas, their sizes, ranging from several hectares to several hundreds of square kilometres, and the desired frequency of the observations is crucial for the monitoring strategy, with regard to its feasibility and the costs.
>
> ***Monitoring methods:*** As the expenses for labour-intense methods such as **'manual' inventories** increase with an increasing area (more samples necessary to ensure representativeness) and

desired frequency of the surveys, the use of **automatically and continuously measuring eddy covariance systems**, which are more expensive in terms of investment costs, might become more economical at a certain point. *The number of sample plots for an inventory or eddy covariance towers within an afforestation area depends on the heterogeneity of the area* (soil, biomass).

Publicly available remote sensing data such as canopy height estimates offer a more cost-efficient alternative for biomass inventories of, particularly, large areas, however, at the cost of the accuracy. Instead, terrestrial laser scanning offers an increased accuracy compared to manual recordings, but might imply higher costs, especially with regard to the instrument. While comparing the costs one has to keep in mind, that an *initial determination of the carbon stock in soil and biomass is essential also for eddy covariance setups*, in order to define a baseline of carbon stock changes.

Measurements of biosphere-atmosphere GHG fluxes are preferably done by means of eddy covariance. Carbon dioxide (CO_2) is the crucial component in afforestation projects in arid zones. Following good practices, methane (CH_4) flux measurement have to be included only at those sites where CH_4 is expected to significantly contribute to the GHG balance (e.g. wet sites). Nitrous oxide (N_2O) flux measurement need to be included at sites where N_2O is expected to significantly contribute to the GHG balance (e.g. agricultural sites or heavily fertilised sites). For the net balance of incoming and outgoing carbon fluxes i) gaseous carbon exchange with the atmosphere and ii) lateral carbon transport comprising particulate organic carbon fluxes such as fertilisation (as an import) or export of biomass (e.g. wood), iii) dissolved carbon flux in waters and iv) lateral transport of soil carbon through erosion should be monitored. For afforestation projects in arid zones it is most probably sufficient to simplify the balance to the first two components.

In addition, basic meteorology, soil condition and solar radiation (including diffuse radiation) should be measured at each site. Solar radiation measurements should include representative short wave albedo measurement. Albedo is important to measure since afforestation tend to change albedo.

In larger project areas (starting from about 100 km^2) CarbonSink+ -effect could be verified. A good proxy, enabling cost effective determination for VOCs and aerosol growth, is air ion size distribution. That can be measured using NAIS (Neutral Cluster and Air Ion Spectrometer). The instrument enables determination of formation rates for ion clusters, neutral clusters and their growth rates as a function of particle size (Kulmala et al. 2012). NAIS, manufactured by Airel Ltd. (Estonia), measures mobility distribution of naturally charged and neutral nanoparticles in high time resolution. The measurement ranges are 2-42 nm and 0.8-42 nm for the neutral clusters and ions, respectively. The NAIS is a robust, field-worthy instrument, which can be operated for extended periods even unattended (Manninen et al. 2010).

For a complete description of CarbonSink+, the VOC emission, aerosol particle growth and diffuse solar radiation can be measured directly. For the measurement of VOC concentration and emission rate, the PTR-MS (Proton Transfer Reaction – Mass Spectrometer) should be used. Aerosol particle size distribution is best measured using DMPS (Differential Mobility Particle Spectrometer). The DMPS system (Aalto et al. 2001) is the standard aerosol particle size distribution monitoring instrument. The DMPS provides a total size range from 10 to 800 nm, which will be complemented by NAIS in the ultra-fine range. The DMPS is system is the backbone of various parameters inferred from the particle size distribution, which are needed in further analysis.

These parameters include

- particle formation and growth rates
- condensable vapor concentration source rates
- vapor condensation sink
- analysis of aerosol formation events, formation event type classification

The DMPS system provides us a direct comparison against the measured condensable vapor concentrations (from precursor measurements) and the effective aerosol size increase that is linked to the abundance of the vapors.

5.1.2 Operational phase

The lower part of the scheme (Fig. 5.1) show the operational phase of the project.

Step 4: The main part of the operational phase is monitoring, i.e. conducting the measurements. Depending on the selected method this part may be seasonal and very labor intensive (manual inventories) or continuous with high level of automation (eddy covariance measurements), or integrating both of them.

Step 5: Both inventory and eddy covariance data need professional post processing and data analysis. This involves quality control, gap filling and some modelling to consider the whole area on interest. After appropriate processing, the eddy covariance data will result in reliable annual greenhouse gas balance of the site. Inventory methods will result in reliable carbon stock values but on limited time scale.

Step 6: The operational phase (measurement -> data analysis -> reporting) will repeat in cycles of e.g. one year.

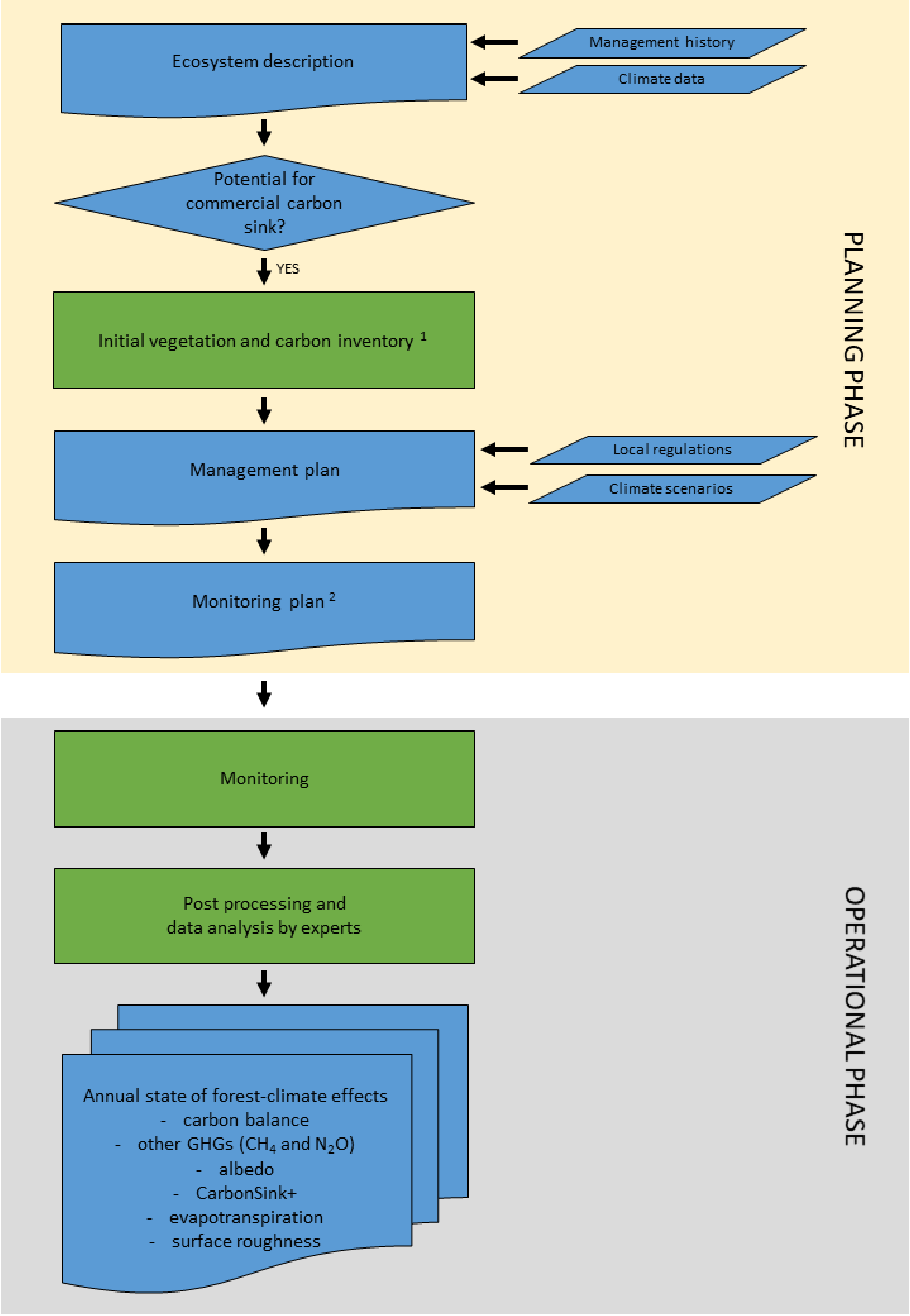


Figure 5.1 Flow chart for a carbon sequestration project.

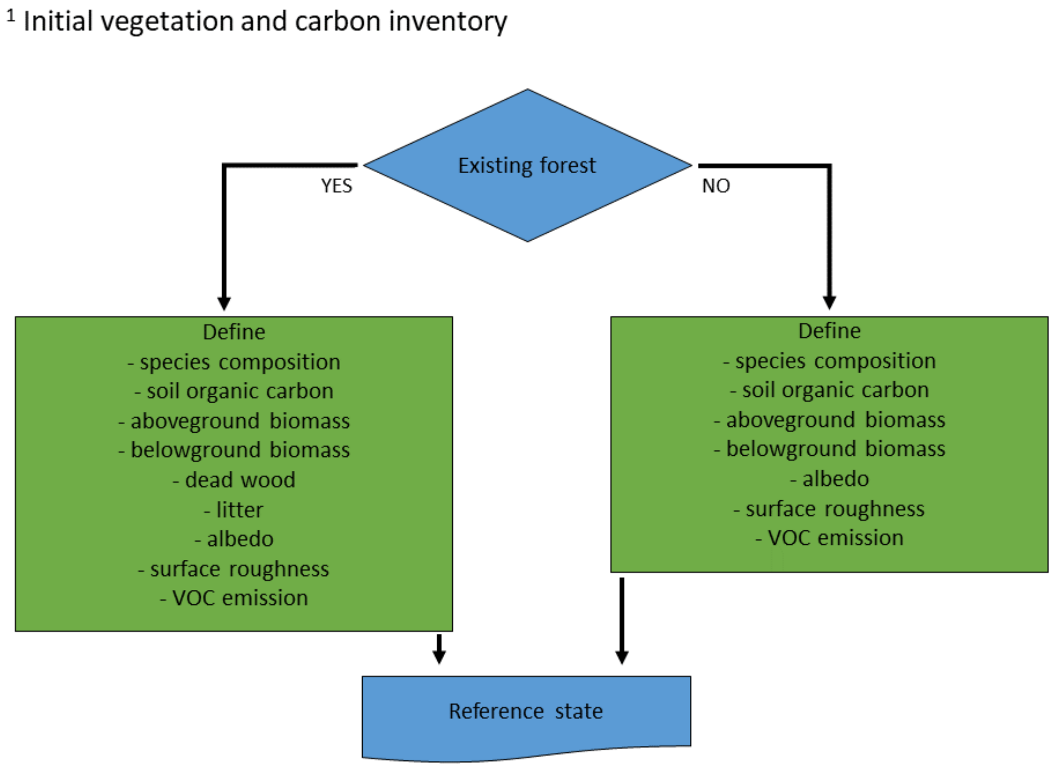
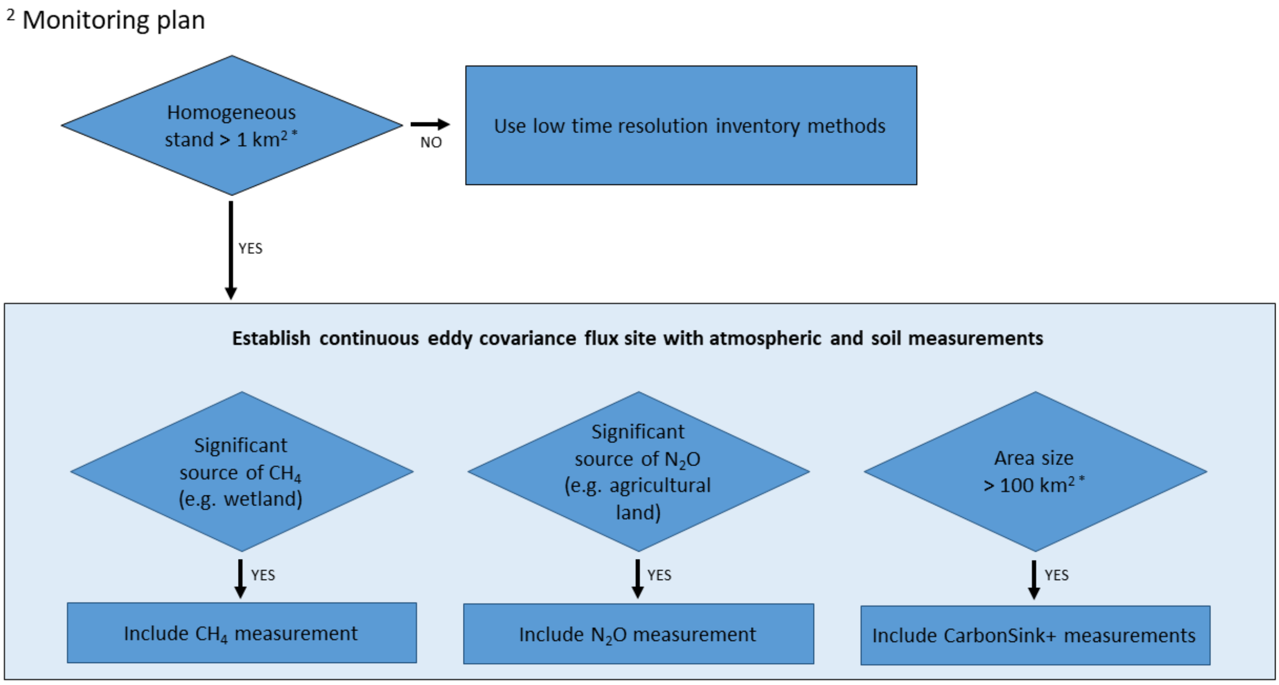


Figure 5.2 Details of initial vegetation and carbon inventory.



* Given areas are order-of-magnitudes only

Figure 5.3 Details of monitoring plan.

5.2 Estimated costs of the measurements

5.2.1 Costs of carbon inventories

Based on Hyytiälä-ICOS station experience, it takes about 200 working hours for field and laboratory staff (> 1 person-month) to conduct a biomass inventory for an eddy covariance footprint sized forest with manual tools, in case suitable allometric functions are already available. Sampling with TLS (terrestrial laser scanning, see Ch2) is more time-efficient, whereby the time needed depends on the forest density. The processing of the data requires specific expertise as so far there is no commercial software available. The instrument price is about 50 000 €.

For a soil organic carbon inventory in an eddy covariance footprint sized forest, including soil sampling in the field, preparation and analysis in the lab about 300 working hours (< 2 person-months) have to be estimated.

5.2.2 Costs of eddy covariance measurements

For carbon balance, a low cost and easy to deploy station can be used. Depending on the ecosystem, other components of the GHG balance, particularly CH_4 and N_2O, must be included as well. Those measurements are technically more demanding and the cost of the measurement infrastructure will be significantly higher compared to CO_2 measurement.

The main components in eddy covariance measurement system are listed below, instrument specifications ‘listed in Appendix 1 and estimated prices indicated in Table 5.1.

- EC: Fast response 3D ultrasonic anemometer and fast response gas analyser(s) to measure turbulent fluxes of the target gases by eddy covariance.
- STORAGE: Slow response gas analyser(s) to measure sub canopy storage change flux of the target gases.
- ENVIRONMENT: Environmental sensors to measure basic meteorology and soil conditions. Meteorological sensors include air temperature and relative humidity, net radiation balance and photosynthetic photon flux density. Air pressure is measured by fast response gas analysers which is sufficient for a basic setup. Soil measurements include soil temperature profile and soil moisture. Depending on the site, soil properties need to be measured on several places and water table depth may be added.
- DATA: Computer, data acquisition, and remote connection. Power supplies and other small electronics are included here.
- ENCLOSURE: Enclosure provides protection against weather and vandalism. Larger cabinet is needed for CH_4 and N_2O gas analysers.
- MAST: Depending on the site and vegetation height a mast of 2-30 meters is needed. A variety of mast solutions are available: From simple poles and lightweight composite masts to heavy lattice masts.
- POWER: Grid power is always preferred. At sites where grid power is not an option, we can operate simple setups (CO_2 measurement) with a solar panel / fuel cell -hybrid solution.

Table 5.1 Costs of the modules needed for eddy covariance system in different configurations. For a complete system, select one option of each module. Presented prices are exclusive of VAT, transportation and customs fees.

MODULE	**OPTIONS**		
EC	$CO_2 + H_2O$ 37 000 €	$CO_2 + CH_4 + H_2O$ 112 000 €	$CO_2 + CH_4 + N_2O + H_2O$ 215 000 €
STORAGE	$CO_2 + H_2O$ 8 000 €	$CO_2 + CH_4 + H_2O$ 15 000 €	$CO_2 + CH_4 + N_2O + H_2O$ 70 000 €
ENVIRONMENT	STANDARD 7 000 €	ADVANCED 20 000 €	
DATA	STANDARD 5 000 €	ADVANCED 8 000 €	
ENCLOSURE	STANDARD 1 000 €	ADVANCED 6 000 €	
MAST	3 m POLE 1 000 €	10 m MAST 5 000 €	30 m MAST 22 000 €
POWER	GRID 1 000 €	OFF-GRID 20 000 €	

Typical eddy covariance setups for selected example sites are given below. The prices are obtained from Table 5.1.

1) Site: Tall forest (20 m), dry soil, grid power available.
Instrumentation: CO_2 flux measurement with 30 m mast.
Cost estimate: 80 000 €

2) Site: Afforested wetland, grid power available.
Instrumentation: CO_2 and CH_4 flux measurements with 10 m mast.
Cost estimate: 140 000 €

3) Site: Afforested field, without grid power.
Instrumentation: CO_2, CH_4 and N_2O flux measurements with 10 m mast, hybrid power solution.
Cost estimate: 260 000 €

The prices do not include detailed planning and construction of the station, which amounts to about one person-month. In addition, about one person-month per year needs to be accounted for maintenance and data analysis. In long-term use instrument replacement costs need to be accounted for. However, due to highly random nature of instrument failures the cost of replacement instruments is difficult to estimate.

The given prices are for a single measurement setup. Substantial cost reductions are expected if multiple similar setups are constructed simultaneously.

The estimated prices of the instrumentation are based on present-day situation, with scientific research being the main market. When commercial carbon sink measurements are widely used the instrument markets will be expanded, leading to significant price reduction. Early pilot projects will accelerate the development.

5.2.2 Costs of CarbonSink+ –measurements

Neutral Cluster and Air Ion Spectrometer (NAIS) measures mobility distribution of naturally charged and neutral nanoparticles in high time resolution. The estimated price of the instrument is 60 000 €. In addition, advanced environmental/meteorological sensors are needed. The estimated price is 20 000 € as given in Table 5.1. For the data analysis, one person-month per year should be included in the costs.

For the complete description of CarbonSink+, the instruments needed are PTR-MS and DMPS. The investment cost for PTR-MS is about 250 000 € to 400 000 € depending on the selected version. For the DMPS, the investment cost is about 70 000 €. Detailed planning and construction of the station amounts to about 3-6 person-months. In addition, significantly increased spare part and labor cost for maintenance of these devices should be taken into account.

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Conclusions and further steps

Markku Kulmala & Tuomo Kalliokoski

The maximum CO_2 concentration in 2018 was over 410 ppm. Right now global CO_2 emissions (41,4 $GtCO_2$ $year^{-1}$) are much higher than global carbon sink (11,7 $GtCO_2$ $year^{-1}$) . Current rate of atmospheric CO_2 concentration increase is > 2-4 ppm $year^{-1}$. The atmospheric concentration of 500 ppm will be crossed within 30 years without both curbing fossil greenhouse gas emissions and enhancing ecosystem carbon sinks. Therefore, global sinks have to be larger than global emissions within next 30 years. In Nordic countries we should be carbon negative by 2035. Afforestation and reforestation provide means for increasing ecosystem sinks. However, restoring carbon storages of ecosystems by planting new trees takes too long. We need to increase also carbon storages in existing forests if we want restrict global warming <1,5°C or even <2°C and avoid too heavy reliance on engineered sinks (e.g. BECCS).

The actions what should be performed now:

- As a first step, the emissions should get levelling off
- Cut emissions as much and as rapidly as possible taking into account also societal and economic impacts
- Enhance sinks
    - Include CarbonSink+ in the estimates. For this we need measurements in other vegetation zones than boreal forests since current understanding is based almost only on Hyytiälä SMEARII measurements.
- Establish a Carbon Market – market place for emitted and sequestrated CO_2 including also sinks
    - Global
    - Private sector
    - Proper observations to verify the sinks

Some parties have proposed the global Carbon Market. We see the establishment of the global **Carbon Market** as one possible method to generate activities for supporting and speeding up climate mitigation. Since the atmosphere is global and does not see any sectors, the global Carbon Market should be seamless.However, this is only one model of possible changes of regulation and more research is needed for covering possible caveats. Carbon Market should also be reflected in the context of three pillars of EU climate policy, i.e. Emission Trading System – Burden Sharing – Land use, Land use change and Forestry. The Carbon Market as a market place should follow three main principles:

- ”Who emits **pays**”
    - This means CO_2 emission reduction obligations to companies. This ”Polluter Pays” principle is well studied in the field of environmental science, economics of environmental management and environmental law. The creation of the Carbon Market system should follow the scientific findings of these fields.

- ”Who has verified sinks **earns**”
    - Central tenets here are the commitment period and permanence of stored carbon. Underlying concept is that the cumulative emissions largely determine the global mean warming. However, timing of emissions has also effect, especially from the perspective of overshooting scenarios (crossing the temperature limit for the period of time).

- ”**Accurate observations** to verify credits”
    - Inventory method could be used if accounting includes only carbon sink and, due to time resolution of measurements, commitment periods are long enough (from decades to 100 yrs). If CarbonSink+ or higher time resolution (from real time to 12 months) are needed then more sophisticated measurement system should be used.

If the framework and protocols of Carbon Market could be formulated following these principles it may increase the possibility to achieve carbon neutral EU by 2050. From the perspective of the leadership in climate policy, Europe should strive for carbon negativity already 2040. EU has well defined climate targets (-40% of GHG emissions by 2030, and carbon neutral at 2050). However, for the greater impact the emphasis on globally scalable measures and technologies could be set inside Carbon Market. Also allowance of CO_2 reduction activities across the sectors and in the 3rd countries (incl. carbon sinks) along Article 6 of Paris Agreement should be included in the Carbon Market system. All these system level protocols of the Carbon Market should be created in the close collaboration of the scientific community, decision makers, and private sector acknowledging the risks for discontinuities in the market mechanism which may result in unwanted phenomena like carbon leakage, or firstcomers gathering highest benefits by accomplishing the easiest mitigation projects (“low hanging fruits”) .

We can measure carbon sink and actually also CarbonSink+ (see chapters, 2,3 and 5).

The international protocols and standards can be developed and they are already partially existing. The present situations is:

- Greenhouse gases: ICOS standards and protocols
- VOCs, aerosols, cloud droplets: ACTRIS protocols
- Clouds, precipitation: WMO and satellites

The ROAD map for further steps to standardize observations and verification methods are:

1. Approval of international standards: Metrology organisations , WMO, IPCC
2. New cheap but accurate instruments: development and construction
3. Verification of carbon sink and CarbonSink+
4. Carbon market - Emission and sink market place(s)
5. Schedule:
   1-3 possible within 24 months after big enough resources available

Globally we need accurate observations & leadership. Pilot projects are needed to establish show cases how to enhance carbon sinks and CarbonSink+. At the same time we need to develop cheap and accurate devices to verify carbon sinks and CarbonSink+. To scale all this up we need international collaboration.

Circa 50 Mkm^2 of boreal forest (or corresponding ecosystem) is needed to reach global carbon neutrality with current level of GHG emissions. With the help of CarbonSink+ the needed area is only 30 Mkm^2. However, in this order of magnitude calculation based on Hyytiälä / SMEAR II data includes significant uncertainties and therefore more observations are needed to verify this and carbon sinks more generally and also to enable accurate models to help verifications.

For accurate observations we need wider and deeper combination of different research infrastructure than current situation. This could be seen as a network of measurement stations with standardized protocols forming Global SMEAR approach with hierarchy of stations. This means collocation of ICOS (Integrated Carbon Observations System, www.icos-etc.eu), ACTRIS (Aerosols, Clouds, and Trace gases Research Infrastructure, https://www.actris.eu), ANaEE (Analysis and Experimentation on Ecosystems, https://www.anaee.com), eLTER (Long-Term Ecosystem Research in Europe, http://www.lter-europe.net) and other research infrastructures under same principles endorsing the best scientific practices and data quality protocols.

Anyhow it is important to take leadership with clear, ambitious vision to establish global carbon market with global Earth observatory.

It is time to go from ideas to implementation.

Appendix 1: Specifications for instruments

Requirements for fast response 3D anemometer

Measurement range: wind components: 0 to ±30 m/s; sonic temperature: ±30°C
Accuracy: horizontal components: 0,1 m/s; vertical component: 0,05 m/s
RMS noise: <0,001 m/s
Sample rate: 10 Hz

Requirements for fast response CO_2/H_2O analyzer

CO_2, H_2O and temperature measured simultaneously in the same sample volume.
Sample rate: 10 Hz

CO_2 analysis specifications

Measurement range: 0 to 1000 ppm
Accuracy: within 1% of reading
RMS noise (@400 ppm, 10 Hz): <200 ppb

Cross sensitivity to H_2O: $<1{,}0 \cdot 10^{-4} \frac{mol_{CO_2}}{mol_{H_2O}}$

Negligible cross sensitivity to other atmospheric trace gases

H_2O analysis specifications

Measurement range: 0 to 50 ppt
Accuracy: within 2% of reading
RMS noise (@10 ppt, 10 Hz): <10 ppm

Cross sensitivity to CO_2: $<1{,}0 \cdot 10^{-1} \frac{mol_{H_2O}}{mol_{CO_2}}$

Negligible cross sensitivity to other atmospheric trace gases

Requirements for fast response CH_4 analyzer

CH_4, H_2O and temperature measured simultaneously in the same sample volume.
Sample rate: 10 Hz

CH_4 analysis specifications

Measurement range: 0 to 20 ppm
Accuracy: within 1% of reading
RMS noise (@2 ppm, 10 Hz): <5 ppb

Negligible cross sensitivity to H_2O and other atmospheric trace gases

Requirements for fast response N_2O analyzer

N_2O, H_2O and temperature measured simultaneously in the same sample volume.
Sample rate: 10 Hz

N_2O analysis specifications

Measurement range: 0 to 4 ppm
Accuracy: within 1% of reading
RMS noise (@0,5 ppm, 10 Hz): <0,5 ppb

Negligible cross sensitivity to H_2O and other atmospheric trace gases

Requirements for air ion and aerosol particle spectrometer

Sample rate: 1 Hz
Measurement size range: 2 to 40 nm for neutral particles and 1 to 40 nm for ions.

Accuracy 10% of concentration at certain size range

VOC concentration analyzers

Sample rate: 0,1 Hz (grab sampling) or 10 Hz (continuous sampling)
Measurement range, sensitivity and accuracy dependent on compound.

Generally, integration times of the order of 1-10 seconds are sufficient for measurements of VOCs volume mixing ratios of the order of 10-100 ppt_v.

Detection limit ranges from a few tens of ppt_v (e.g. 18 ppt_v for benzene) to several hundreds of ppt_vs (300 ppt_v for methanol, which has a high background signal).

PTR-TOFMS has a sensitivity for sesquiterpenes 20 ppt_v with a dwell time of 10 minute or more.

Requirements for aerosol particle concentration analyzers

Sample rate: 1 Hz
Measurement range: 0,01 to 10000 particles per cm^3
Concentration accuracy: $N^{1/2}$ when N is total particle concentration in certain size range

Weather sensors

Air temperature

Measurement range: -50°C - 50°C
Accuracy: ±0,1°C
Precision: ±0,1°C

Response time: 60 s

Air relative humidity

Measurement range: 5 – 100%
Accuracy: ±3%
Response time: 60 s

Air pressure

Measurement range: 900 – 1100 hPa (range should be modified for high altitude sites)
Accuracy: ±0,5 hPa
Precision: ±0,5 hPa
Response time: 60 s

Requirements for net radiation components, PAR radiation, global radiation and diffuse radiation

Accuracy: 10%