Natural and social dimensions of forest carbon accounting

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Wilhelm Dubber

LUND UNIVERSITY

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Abstract

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Several approaches are available for monitoring of forest carbon fluxes. Sample based field inventories form the basis for the collection of forest information in most countries. Remote sensing offers the ability to map forests with high resolution, and process-based computer models can simulate the behavior of forest ecosystems and predict their response to future climate and changes in management. The aim of this thesis is to study the impact of different approaches on forest carbon monitoring, and suggest how they can be combined to enhance the results by utilizing the strengths of the respective methods. The potential of technological advances in remote sensing and modeling application is related to the needs of the Swedish forestry sector identified by interviews, and an approach is presented for verifying carbon flux estimates versus tower measurements of carbon dioxide concentrations. The results highlight the differences between methodological approaches for forest carbon monitoring, both regarding their impact when estimating regional carbon budgets and implications at the international political arena. Process-based modeling informed by remote sensing and/or field inventory data is shown to be an efficient tool for simulating the spatial distribution of Swedish forest carbon fluxes that can deliver the demands for increased forest information.

Key words: forest carbon, boreal forest, LPJ-GUESS, Biome-BGC, remote sensing, REDD+

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III. Dubber W., Monteil G. & Smith B., Spatio-temporal attribution of forest contribution to country-scale variation in atmospheric CO_2. *Submitted*

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Paper contributions

I. WD contributed equally to the development of the manuscript and to the literature research. FZ lead the writing, with WD mainly contributing to the methodology and results sections, as well as formatting and fact-checking throughout the entire manuscript.

II. WD performed the model simulations, all analyses and led the writing of the manuscript with input from the other authors.

III. WD set up and performed the ecosystem model simulations and spatial disaggregation using land cover data. GM performed and analyzed the transport model results. WD led the overall analysis and wrote the manuscript with input from co-authors.

IV. WD performed the interviews and literature review, and wrote the manuscript with input from FL.

Abstract

Global forests store large amounts of carbon both in living biomass and in the soil. The ability of forests to counteract climate change by acting as carbon sinks have been recognized in global climate politics, such as the 2015 Paris agreement which calls for national commitments to reduce greenhouse gas emissions. Sweden is one of many countries who have pledged ambitious climate goals, promising to achieve net zero emissions by 2045. To achieve this goal, greenhouse gas emissions must be balanced by uptake of carbon dioxide in natural ecosystems such as forests. Active management is important in determining the forests' ability to mitigate climate change, but the trade-off between climate benefits, economic values and biodiversity have to be considered. To be effective, climate related decision-making requires an understanding of forest dynamics as well as knowing the spatial and temporal distribution of forest carbon sinks and sources.

Several approaches are available for monitoring of forest carbon fluxes. Sample based field inventories form the basis for the collection of forest information in most countries. Remote sensing offers the ability to map forests with high resolution, and process-based computer models can simulate the behavior of forest ecosystems and predict their response to future climate and changes in management. The aim of this thesis is to study the impact of different approaches on forest carbon monitoring, and suggest how they can be combined to enhance the results by utilizing the strengths of the respective methods. The potential of technological advances in remote sensing and modeling application is related to the needs of the Swedish forestry sector identified by interviews, and an approach is presented for verifying carbon flux estimates versus tower measurements of carbon dioxide concentrations. The results highlight the differences between methodological approaches for forest carbon monitoring, both regarding their impact when estimating regional carbon budgets and implications at the international political arena. Process-based modeling informed by remote sensing and/or field inventory data is shown to be an efficient tool for simulating the spatial distribution of Swedish forest carbon fluxes that can deliver the demands for increased forest information.

Sammanfattning

Världens skogar lagrar stora mängder kol både som levande biomassa och i marken. Skogarnas förmåga att motverka klimatförändring genom att fungera som kolsänkor har erkänts inom global klimatpolitik, till exempel Parisavtalet från 2015 vilket uppmanar länder att minska sina utsläpp av växthusgaser. Sverige är ett av flera länder med ambitiösa målsättningar och har lovat att inte ha några nettoutsläpp efter 2045. För att uppnå detta mål krävs att utsläpp av växthusgaser balanseras av upptag av koldioxid i de naturliga ekosystemen som exempelvis skogsmark. Aktiv skötsel kan starkt påverka skogens förmåga att bromsa klimatförändringar, men balansen mellan klimatpåverkan, ekonomiska intressen och värden kopplade till biologisk mångfald måste beaktas. För att kunna fatta effektiva klimatrelaterade beslut krävs en förståelse om skogens processer och kännedom om skogliga kolkällor och sänkors variation över tid och rum.

Det finns ett flertal tillvägagångssätt för att övervaka skog. Provytebaserade fältinventeringar utgör grunden i de flesta länders skogsinventeringar. Fjärranalys ger möjlighet att kartlägga skogarna med hög upplösning, och processbaserade datormodeller kan simulera hur skogliga ekosystem beter sig och förutsäga deras påverkan av framtida klimat och ändrad skogsskötsel. Syftet med denna avhandling är att studera vilken inverkan olika tillvägagångssätt för att kvantifiera skogens kolflöden har, och att föreslå hur de kan kombineras för att förbättra resultaten genom att utnyttja egenskaperna hos respektive metod. Möjligheterna av nya tillämpningar inom fjärranalys och modellering sätts i relation till behov som identifierats genom en intervjustudie inom den svenska skogssektorn, och en metod presenteras för att verifiera beräknade kolflöden genom jämförelser med mastbaserade mätningar av atmosfäriska koldioxidkoncentrationer. Resultaten belyser skillnader som finns, både för metodernas påverkan av resultaten för lokala kolberäkningar och deras implikationer inom internationell klimatpolitik. Process-baserad modellering, understödd av data från fjärranalys och/eller fältinventeringar, visas vara ett lämpligt verktyg för att beskriva den rumsliga variationen av kolflöden inom svensk skog och som kan tillgodose ett ökande behov av skoglig information.

Introduction

Forests and climate

Global warming is a dominant part of climate change, and has potentially devastating consequences on both ecosystems and human society (Pachauri et al. 2014). It is caused by elevated concentrations of greenhouse gases (GHGs) in the atmosphere, of which the most prominent is carbon dioxide (CO_2). Long-term measurements of atmospheric CO_2 at the Mauna Loa observatory, Hawaii, show a steady increase in concentrations since the start in 1958 (Figure 1). CO_2 is released to the atmosphere mainly through burning of fossil fuels, but also from emissions related to land use change. Le Quéré et al. (2018) puts annual emissions from these sources to 9.4 and 1.3 Pg C respectively. All emitted CO_2 does not stay in the atmosphere, but instead ends up in the ocean or terrestrial ecosystems. Growing forests absorb CO_2 from the air and store it as carbon in living biomass and in forest soils. They have been estimated to capture 2.4 Pg C globally every year (Pan et al. 2011), which helps to limit the rate of global warming. Carbon storage is highly sensitive to changes both in climate and human influence, and understanding the dynamics of forest carbon fluxes is crucial when combating climate change (Law et al. 2018). Correctly managed, forests have the potential to compensate for large parts of anthropogenic greenhouse gas emissions by increased uptake and storage of atmospheric CO_2. This potential is globally acknowledged and forest management is a key concept in many political arenas and international agreements regarding climate change, such as the UNFCCC, Kyoto protocol, 2015 Paris agreement and REDD+ framework.

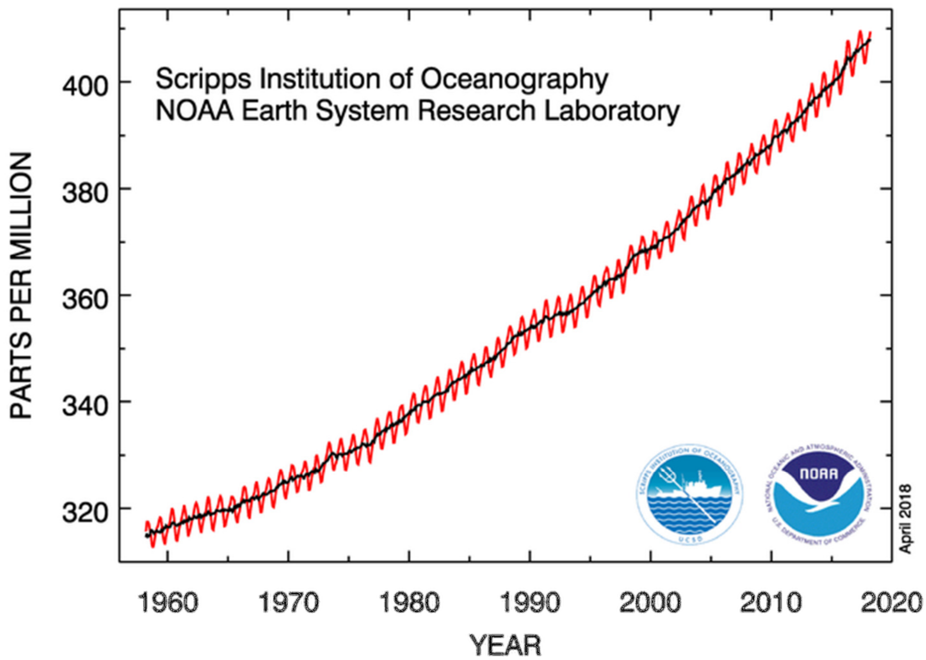

Figure 1. Atmospheric CO_2 concentrations measured at Mauna Loa Observatory, Hawaii.

The forest carbon cycle

Forests absorb atmospheric CO_2 through the process of photosynthesis. Sunlight energy is captured by the leafs and used to transform CO_2 and water to oxygen and sugar. The rate of carbon uptake by the forest is called gross primary productivity (GPP). Some of the absorbed sugar is used for growth and maintenance in a process where carbon is emitted back as CO_2 to the atmosphere (autotrophic respiration). The remaining carbon fraction is the net primary productivity (NPP) which is stored as biomass in the tree. The biomass is turned over to litter, at various rates for different components. Decomposition of litter and other dead organic matter releases further carbon to the atmosphere (heterotrophic respiration). The remainder is the net ecosystem exchange (NEE) which is the long-term storage of carbon in forest ecosystems. This denotes carbon stored both as tree biomass and in the soil, as well as biomass that is harvested. Harvested biomass can be used for a variety of products that also store carbon over time, such as wood used for building material. The Swedish forests currently accumulate 9.9, 3.2 and 1.8 Tg C every year in biomass, soil and harvested wood products respectively (NIR 2017).

Beyond CO_2 there are several other greenhouse gases that influence the climate and are part of the forest fluxes, such as methane and nitrous oxide. Focus in this thesis, as in most other studies, are on CO_2 since this is the dominant GHG (IPCC 2015) and the main impact of forests on the climate are through uptake and release of CO_2. Some forest emissions of methane and nitrous oxide occurs however, mainly from drained organic soils (He et al. 2016), which can be important when considering e.g. the impacts of forest management (Vestin 2017).

Forest monitoring - different frameworks

Large scale forest monitoring is fundamental if we want to understand the links between forests and climate. It is also needed for predicting and evaluating the effects of forest management on the carbon balance and the potential to increase the climate benefits of forests. For this reason, most countries have or are on their way to implement a national system for monitoring of their forests. Depending on their status and location in the world countries are generally part of either of two frameworks for greenhouse gas accounting with reporting requirements, each with its own rules and objectives.

The UNFCCC (United Nations Framework Convention on Climate Change) requires industrialized countries (referred to as annex 1 countries, currently 43 entities including the EU) to submit annual summaries of national greenhouse inventories, in which both land use change and emissions/uptake from forest land are included (UNFCCC 2013). The objective is observation of forest carbon fluxes, providing comparable estimates of national GHG emissions to follow trends and progress towards global and national goals of reduced emission.

For developing countries, the dominant framework is REDD+ (Reduced Emissions from Deforestation and forest Degradation). This is an incentive based scheme to compensate developing nations for projects that reduce carbon emissions from forest based activities and enhance forest carbon stocks. These projects range in implemented scale from local to national. To evaluate and verify the outcome of these projects, participant nations in REDD+ projects are encouraged and often sponsored to develop national forest monitoring systems (UNFCCC §71 of decision 1/CP.16). The objective within REDD+ is to relate carbon stocks with active management, providing support for claimed benefits of the implemented projects. Unlike the requirements for annex 1 countries, REDD+ focus exclusively on forests but also include a variety of non-carbon objectives in the monitoring schemes such as biodiversity and social impacts. There are currently 64 countries linked to the United Nations REDD+ programme UN-REDD, which is one of many actors in the REDD+ community that provide guidance and financing for REDD+ projects.

Forests have traditionally been monitored on a national scale by sporadic surveys or field inventories with the aim to supply information to the forest industry about standing volume and growth. With the introduction of requirements for monitoring forest carbon, existing inventories had to be adapted and new ones developed (Fridman et al. 2014). Apart from implementing and standardizing field inventories, many countries also adopted new techniques that have become available by technological advances. Remote sensing allow forests to be studied from afar, e.g. using aerial photography or satellite observations (McRoberts and Tomppo 2007), and computer driven models can be used to simulate the behavior of forest and forest soils (Tuomi et al. 2011).

The intergovernmental panel on climate change (IPCC) is an international body for assessing the science related to climate change. They provide regularly updated assessments (IPCC 2006) which include details on how carbon monitoring should preferably be performed, with methods to use divided into tiers based on details and accuracy. The guidelines have a generally free form, allowing countries to choose their own methods of carbon monitoring as long as these are transparent and comparable. For REDD+ there are additional guidelines (FAO 2013) that give fixed suggestions on how to implement a monitoring system based on field inventories and remote sensing. These guides are followed strictly by many REDD+ participants, with modifications depending on national circumstances.

The choice of method used for monitoring forest carbon has a clear impact on the results. All methods have their inherent limitations in what they can measure and at which scale, resolution and accuracy. Due to the heterogeneity of forest carbon fluxes, different methods can also result in large discrepancies between their carbon estimates (e.g. Mitchard et al. 2014).

Aim and objectives

The intention of forest monitoring is often not only to find out the quantity of forests and how fast it grows, but also understanding the dynamics that govern and influence growth and related processes. In a changing climate, increasing attention has also been focused on predicting how forest processes and carbon balance might change in the future. Different approaches to forest monitoring have their own unique limitations and potentials for capturing the various aspects of forests, carbon uptake and emissions. Understanding the conditions for existing approaches can help us develop and improve methods to achieve better results.

This thesis aims at investigating the potentials of different methods used for forest carbon accounting from a national perspective, to evaluate and improve the use of field inventory, remote sensing and process modelling for the purpose of national forest carbon accounting, as well as studying political implications of the use of these methods. The main objectives were to:

- Link methods used in national carbon inventories with political discourses in REDD+.
- Calculate the CO_2 balance of Swedish forests for the period 2000-2010 with different methods.
- Compare the results of methods for carbon accounting to understand the underlying reasons for discrepancies.
- Suggest improvements to forest monitoring methods based on combinations of approaches and the use of multiple data sources.

Forest carbon monitoring methods

Field inventories

Field inventories means that observation of the forest takes place on site. Inventorying based on statistical sampling techniques were introduced throughout the twentieth century and now form the basis for most national forest inventories (Tomppo et al. 2010). Common variables to measure include tree species, height and diameter/circumference, but can include a variety of other data.

The Swedish National Forest Inventory (SNFI) is a continuous source of statistics on forest structure and composition as well as a variety of related data such as understory and quantity of dead wood, reaching back to the early 20th century. About 6 000 forest plots are currently inventoried each year. Of these, 4 000 are permanent plots that are resampled every five years, providing a basis for estimating change over time. The results are presented annually on a county basis, available freely online at https://www.slu.se/riksskogstaxeringen.

Field inventories forms the base of our understanding of forests, which is required for parameterization and calibration of virtually all other approaches to forest monitoring. There are two main limitations to field inventorying of forests. They are sample based, which means that they only cover a small fraction of total forest areas. This is suitable for producing statistics on a national scale, but makes it hard to accurately capture events that are limited in space and time such as forest disturbances (e.g. harvest, fire, insect infestations). Field inventories are also limited to CO_2 when estimating forest carbon fluxes. The common approach is to use the stock-change method, which means that total carbon stock is measured at two points in time and carbon flux is estimated as the difference between the two measurements interpolated over time. Due to forest carbon fluxes being much smaller in size compared to carbon stocks, small measurement errors propagate to cause large uncertainty in flux estimates (Ståhl et al. 2003). This is especially true when monitoring forest soil carbon (Muukkonen et al. 2009).

Remote sensing

Remote sensing refers to platform-based observation of forests, commonly by sensors mounted on aircraft or satellites. Active sensors such as LiDAR are useful for estimating forest structure variables, e.g. height, volume and tree density. Multi-spectral data on forest reflectance can be used for mapping forest cover extent and forest stratification or species identification. It can also provide information on foliage quality (e.g. leaf area index, nitrogen content or photosynthetic activity) which can be related to forest health, phenology and productivity. Of special interest when studying forest carbon balances are light use efficiency (LUE) modelling (Prince 1991). LUE is based on the concept that forest productivity (GPP) is proportional to the amount of absorbed photosynthetically active radiation (APAR). APAR is the product of incoming PAR and the fraction that is absorbed by vegetation (fPAR), both of which can be derived from remotely sensed data. Conversion between APAR and GPP depends on the light use efficiency factor, ε, which varies depending on e.g. tree species and stress related factors (Potter et al. 1999, King et al. 2011). Examples of applied LUE modelling is the MODIS product MOD17A2 (Running et al. 2015) which contains 8-day values of global GPP and annual global NPP with a 1km spatial resolution.

Remote sensing is useful for large-scale observation of forests due to the ability to provide spatially detailed, full coverage, wall to wall maps of forest data. For satellite-based observations the temporal resolution is generally very high, ranging between daily to monthly depending on the spatial resolution of the data gathered but also on e.g. availability of cloud-free images. These qualities makes remote sensing a suitable complement to field inventories, with the added ability to map the dynamics of small-scale changes in forest cover and quality. Due to the full coverage provided by remote sensing it is commonly used to extrapolate the results of field inventories. One such application is the Swedish kNN forest dataset ("SLU forest map", Reese et al. 2003). This is an extrapolation of forest properties such as species, age and volume, based on spectral proximity of remotely sensed data to inventory plots from the Swedish national forest inventory.

Ecosystem modelling

Process-based ecosystem models use a conceptual understanding of forest processes such as photosynthesis, respiration and nutrient allocation to predict carbon fluxes based on input climate data and information on site conditions. Their focus on accurately describing the mechanics of forest growth makes them suitable for predicting response to climate change or new management, and able to contribute with an increased understanding of cause and effect in forest dynamics.

This thesis features two different ecosystem models, Biome-BGC (Kimball et al. 1997, Golinkoff 2010) and LPJ-GUESS (Smith et al. 2014). Both models simulate biogeochemical cycles of forest vegetation driven by climate variables and nitrogen deposition. Both models also have disturbances occurring at fixed intervals representing natural events like severe storms or forest management. The main difference is in how vegetation is represented. In Biome-BGC there is only one parameterization of the vegetation for each model run, representing average values of a biome (White et al 2000) or a specific species. In LPJ-GUESS, vegetation is represented as species and age specific cohorts, which allows for simulation of plant dynamics such as establishment and competition for light and soil resources (Smith et al. 2001).

Paper summaries and results

Forest monitoring in REDD+

REDD+ is not a single institution, but a mechanism aimed at offering financial incentives for developing countries to reduce their emissions from forested lands. Money are gathered through funds and used to finance local and national initiatives. The multitude of funds available means that several actors are involved in the shaping of REDD+, including large ones such as the United Nations and the World Bank but also a multitude of national governments, companies and NGOs (non-governmental organizations). This complex governance system has helped to frame REDD+ to including not only forest carbon but also other related values such as biodiversity and local livelihood, and to consider the social impacts of sponsored initiatives. But it also risks to undermine values such as legitimacy and power-balance of REDD+ actors and stakeholders (Zelli and Van Asselt 2013).

To navigate this multitude of actors and to identify common ideas and values that shape the REDD+ governance, the concept of discourse analysis (Hajer 1995) can be used. In our paper I, we suggest a framework for using discourse analysis to identify dominant storylines (i.e. specific sets of common ideas and values) related to the use and implementation of a particular monitoring practice in the design of national forest monitoring systems. We applied this framework on the reports (R-PPs) of eight countries distributed across Africa, south-east Asia and South America for various aspects of their monitoring systems, such as the relative focus on remote sensing vs field inventories and the implementation of non-carbon monitoring and participation. Our results show a heavy reliance on remote sensing, which is in accordance with the UN-REDD guidelines. There is a high variation across countries regarding suggested field inventories, mainly depending on the national history and previous implementations of forest inventories. The dominant storylines identified were "techno-managerial" and "carbon commodification", which were present across most country reports. This indicates that, despite an increasing attention to co-benefits of biological and social values, REDD+ is still dominated by a carbon-centric view on forests.

Case study: Swedish forests and forestry

Paper II, III and IV in this thesis focus on the Swedish forests as a case study. It is an interesting and suitable case study regarding forest monitoring due to Sweden's extensive forests and ambitious climate aims. About 69% of the Swedish land area is covered by forests, of which most are managed. The dominating species are Picea abies, Pinus sylvestris and various species of Betula, constituting 41%, 39% and 12% respectively of total forest volumes (Nilsson and Cory 2017). Main ownership structures are private persons (330 000 individuals, either directly or through economic associations), private companies and the state, owning 50%, 25% and 20% of the forest area respectively (Christiansen 2014). The Swedish government has recently established a new framework on climate politics ("Klimatpolitiskt ramverk", governmental proposition 2016/17:146). It contains goals for reducing greenhouse gas emissions, with the aim that Sweden shall reach net zero emissions by 2045 and negative net emissions afterwards. These goals rely on active forest management to compensate for emissions from e.g. fossil fuels.

Paper II and paper III analyze the carbon fluxes of Swedish forests. Paper II compares three different methods for calculating forest net primary productivity (NPP) on a county basis, with each method connected to one of the approaches of field inventory, remote sensing and process-based modelling. Forest standing volumes and growth from the SNFI were transformed to carbon uptake using biomass expansion factors from Lehtonen et al. (2004) and turnover rates from Liski et al. (2006). The MODIS NPP product (MOD17A3) were used for the remote sensing approach, with NPP values weighted based on forest cover data from the CORINE 2000 land-cover data set (Büttner et al. 2004). Process-based modelling of the forest NPP were performed with the ecosystem model BIOME-BGC.

Despite the methods being chosen to represent the different approaches of field inventory, remote sensing and process-based modelling, neither is independent of the others. The Biome-BGC model uses tree species and age distribution obtained from the SNFI, and the MODIS algorithm for calculating NPP includes parameters derived using the Biome-BGC model. Scenario-based sensitivity tests showed that the interdependence between Biome-BGC and SNFI only had minor influence on the results, since the spatial variability of model NPP were much more dependent on climate input and latitude than on forest composition. The linkage between MODIS and Biome-BGC were likely stronger according to the sensitivity tests, but the produced NPP values still showed large discrepancies in spatial variation.

The results showed a large variation in NPP values between the three methods used. National forest NPP obtained were 0.50, 0.59 and 0.35 kg C m-2 y-2 for the

SNFI, MODIS and Biome-BGC methods respectively, calculated as an average over the time period 2000-2009. When comparing NPP on a county basis, values from the Biome-BGC simulations showed a much weaker latitudinal trend compared to the other two methods with values in southern Sweden only half of those obtained from the SNFI method (Figure 2). The model captured most of the spatial variation of the SNFI values however, indicating that it can be suitable for simulating Swedish NPP given proper calibration. The MODIS NPP values were much higher than the other two methods in northern Sweden, likely due to influence of understory vegetation. The county of Gotland was an outlier for both the Biome-BGC and MODIS methods, where these overestimated the NPP by 50% and 180% respectively. This highlights the importance of local soil conditions for model-based approaches, since this is the main differentiating factor between Gotland and mainland Sweden.

Differences in results can partly be explained by methodological approaches. E.g. neither the SNFI or the Biome-BGC method considers NPP of understory vegetation, whereas this is visible by the MODIS sensors and can explain why the MODIS NPP is higher in northern Sweden where trees are more sparse and understory constitute a larger part of total NPP (O'Connell et al. 2003). Satellite based estimates of fPAR also tends to be saturated at high forest stand density (Birky 2001), which may explain the lower MODIS values in high-NPP counties.

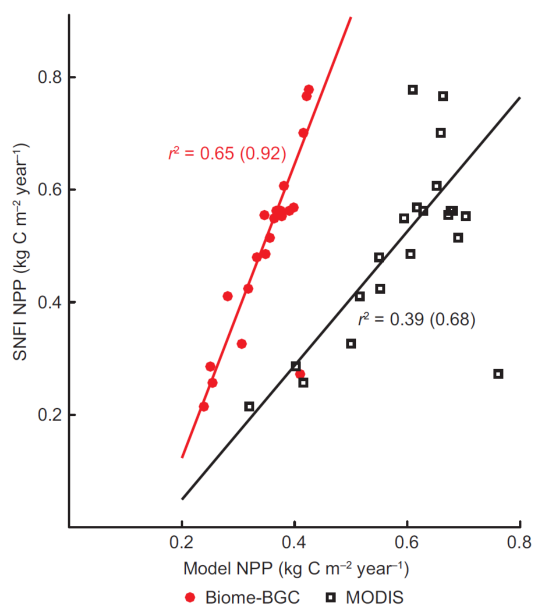

Figure 2. Net primary productivity calculated using the Biome-BGC and MODIS methods described in paper I, compared against NPP from the SNFI method. R^2 values written inside parantheses were derived for Sweden, excluding the county of Gotland as an outlier.

Paper III addresses the issue of validating regional-scale carbon flux estimates, and this time focus on the total forest carbon balance (NEE) instead of forest productivity (NPP). We present a method where Swedish forest NEE is calculated using a combination of process-based modelling (LPJ-GUESS) and data from remote-sensing based extrapolations of field inventories (the SLU forest map). The resulting NEE map was validated using atmospheric transport models to calculate daily footprints for a tower measuring high-altitude (100m above ground) CO_2 concentrations. By integrating the forest NEE, together with other sources of CO_2, across the footprint we could compare the contributing factors to atmospheric CO_2 and verify our total of calculated CO_2 concentrations by comparisons with tower measurements.

The fore flux were shown to dominate the footprint contribution with twice the size compared to other Swedish sources, reaching above 90% during peak growing season (Figure 3). Comparisons with tower data (Figure 4) showed a good agreement with our modelled values of atmospheric concentrations (daily r^2 of 0.69). The timing of the largest discrepancies coincide with peak amplitude of atmospheric concentrations ($RMSE_{June}$ = 3.6 ppm, $RMSE_{August}$ = 5.78 ppm) indicating that main error contributions originate in the calculated background fluxes from outside of our study area. Comparison between modelled forest NEE, average annual values 2000-2005 summed for all of Sweden, and values calculated based on reported forest CO_2 uptake showed a good agreement as well with 28.5 Tg C compared to 33.6 Tg C respectively.

The study focused on atmospheric CO_2 measurements from the tower located in Norunda (60°05′N, 17°29′E). Due to its location in central Sweden it gives a good representation of average forest CO_2 fluxes and minimizes contributions from neighbouring countries. The study can be expanded to include two other towers located in southern and northern Sweden. Due to the locations of these towers, including them can provide a good way to evaluate model performance and flux contributions across different parts of Sweden, but it would also require to expand the modelling of forest NEE across national borders to account for the larger proportion of these tower footprints located outside Sweden.

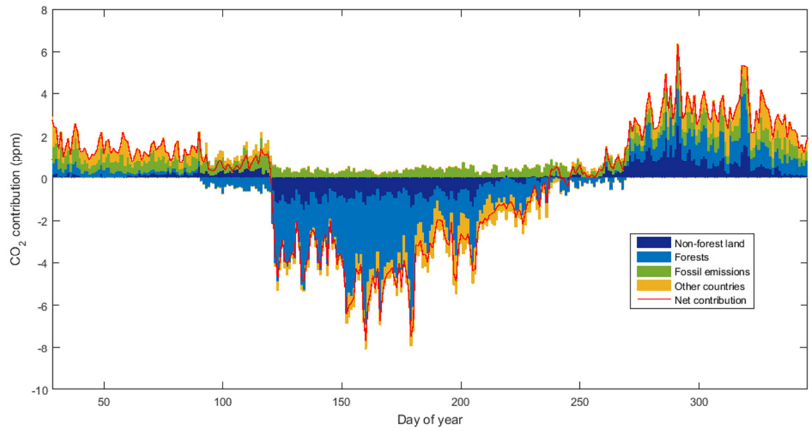

Figure 3. Modeled footprint contributions to atmospheric CO_2 concentration at the tower location, partitioned into component contributors. Values are daily averages across the years 2000-2005. Category 'other countries' refers to countries except Sweden within the footprint area.

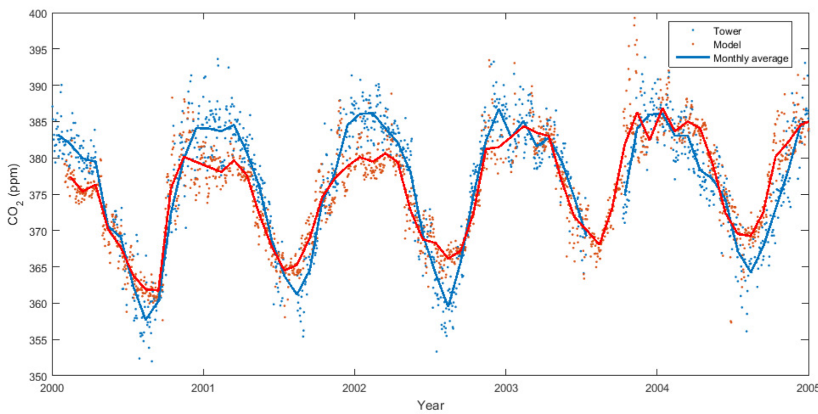

Figure 4. Daily and monthly CO_2 concentrations from tower measurements and calculated values using a transport model. The gap in late summer 2003 is due to low quality tower data.

Paper IV looks at the information needs of the forest sector in Sweden. Interviews were performed with seven key persons working with forest, environment and climate change among forest companies, governmental institutions, and a NGO. The aim was to identify common topics of interest where forest information is lacking. We then addressed how this information may be obtained, focusing on solutions based on remote sensing and process-based modelling.

From the answers of the interviews, three main topics of common interest were identified: high-resolution forest statistics, forest damages and substitution potential of the Swedish forests. Advances in remote sensing capacity, such as regular national LiDAR scanning and the new Sentinel satellites will provide more information about the forests. Improved resolution and return time will give us a better view of the forest landscape and help tracking small-scale events such as insect attacks. For a better understanding of forest interactions with climate change the use of process-based models is likely the best approach. Integrating ecosystem modelling with disturbance, management and biodiversity will give us the tools to understand and guide the forest towards the desired goal, and to weight in the possible trade-offs that are necessary. There are still several aspects of the involved processes that lacks proper understanding and that needs further empirical studies from all levels between leaf and ecosystem.

Conclusions and outlook

Choice of method for monitoring forest carbon makes a difference, both on the results and in a political sense. Our results showed that, despite a growing rhetoric focused on the importance of co-benefits and social safeguards, the REDD+ arena is still dominated by a carbon-centric view. It is concluded, however, that our study only encompassed a selection of monitoring proposals. Future studies would benefit from looking at the actual implementation of the national monitoring systems and how these evolve over time. By increasing the number of countries used as case studies, research could also improve in complexity by accounting for the influence of national attributes such as economic development and size of the forestry sector.

The spatial variation of Swedish forest carbon fluxes can be simulated on a regional scale by process-based models informed by external data on forest composition and distribution, with satisfying results. To provide accurate estimates of the size of NPP, proper calibration is recommended. This can be done using e.g. measurement series obtained from flux towers.

Tower measurements of atmospheric CO_2 concentrations can serve as validation of spatially explicit estimates of forest carbon fluxes, by utilizing a multiple-modelling approach to integrate the fluxes across the towers country-scale footprint. Higher quality of the evaluation can be achieved by increasing the number of towers included in the study and by improving the accuracy of both forest and non-forest carbon flux sources.

New sources of forest information, such as data obtained from the recent and scheduled Sentinel satellites, can improve our understanding of forest dynamics. Process-based models are an important tool in this process as they can help transform information on forest structure and quality to estimates of carbon fluxes, and predict the future behaviour of forests in response to climate change, management and disturbances. Focusing on how to integrate multiple-source data and process-modelling to best utilize their respective strengths will facilitate informed policymaking and management decisions to respond to the challenges of climate change.

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References

Birky A.K. 2001. NDVI and a simple model of deciduous forest seasonal dynamics. *Ecol. Modell.* 143: 43-58.

Büttner G., Feranec J., Jaffrain G., Mari L., Maucha G. & Soukup T. 2004. The CORINE land cover 2000 project. *EARSeL eProceedings* 3: 331-346.

Christiansen L. 2014. *Skogsstatistisk årsbok 2014*. Jönköping: Swedish Forest Agency.

Fridman J., Holm S., Nilsson M., Nilsson P., Ringvall A. H. & Ståhl G. 2014. Adapting national forest inventories to changing requirements – the case of the Swedish National Forest Inventory at the turn of the 20th century. *Silva Fennica* 48

Golinkoff J. 2010. *Biome BGC version 4.2: theoretical framework of Biome-BGC*. Numerical Terradynamic Simulation Group, College of Forestry and Conservation, University of Montana, Missoula, MT.

Hajer M.A. 1995. *The politics of environmental discourse: ecological modernization and the policy process*. Oxford: Clarendon Press.

He H., Jansson P.-E., Svensson M., Björklund J., Tarvainen L., Klemedtsson L. & Kasimir Å. 2016. Forests on drained agricultural peatland are potentially large sources of greenhouse gases–insights from a full rotation period simulation. *Biogeosciences* 13: 2305-2318.

IPCC. 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Hayama: Institute for Global Environmental Strategies.

IPCC. 2015. *Climate change 2014: mitigation of climate change*. Cambridge: Cambridge University Press.

Kimball J.S., Thornton P.E., White M.A. & Running S.W. 1997. Simulating forest productivity and surface–atmosphere carbon exchange in the BOREAS study region. *Tree physiology* 17: 589-599.

King D.A., Turner D.P. & Ritts W.D. 2011. Parameterization of a diagnostic carbon cycle model for continental scale application. *Remote Sensing of Environment* 115: 1653-1664.

Law B.E., Hudiburg T.W., Berner L.T., Kent J.J., Buotte P.C. & Harmon M.E. 2018. Land use strategies to mitigate climate change in carbon dense temperate forests. *Proceedings of the National Academy of Sciences*: 201720064.

Le Quéré C., Andrew R.M., Friedlingstein P., Sitch S., Pongratz J., Manning A.C., Korsbakken J.I., Peters G.P., Canadell J.G. & Jackson R.B. 2018. Global carbon budget 2017. *Earth System Science Data* 10: 405.

Lehtonen A., Mäkipää R., Heikkinen J., Sievänen R. & Liski J. 2004. Biomass expansion factors (BEFs) for Scots pine, Norway spruce and birch according to stand age for boreal forests. *For. Ecol. Manage*. 188: 211-224.

Liski J., Lehtonen A., Palosuo T., Peltoniemi M., Eggers T., Muukkonen P. & Mäkipää R. 2006. Carbon accumulation in Finland's forests 1922–2004–an estimate obtained by combination of forest inventory data with modelling of biomass, litter and soil. *Ann. For. Sci.* 63: 687-697.

McRoberts R.E. & Tomppo E.O. 2007. Remote sensing support for national forest inventories. *Remote Sensing of Environment* 110: 412-419.

Mitchard E.T., Feldpausch T.R., Brienen R.J., Lopez-Gonzalez G., Monteagudo A., Baker T.R., Lewis S.L., Lloyd J., Quesada C.A. & Gloor M. 2014. Markedly divergent estimates of Amazon forest carbon density from ground plots and satellites. *Glob. Ecol. Biogeogr.* 23: 935-946.

Muukkonen P., Häkkinen M. & Mäkipää R. 2009. Spatial variation in soil carbon in the organic layer of managed boreal forest soil—implications for sampling design. *Environ. Monit. Assess*. 158: 67-76.

Nilsson P. & Cory N. 2017. *Skogsdata 2017*. Umeå: Dept. of Forest Resource Management, Swedish University of Agricultural Sciences.

NIR. 2017. *National Inventory Report Sweden 2017*. Stockholm: Naturvårdsverket.

O'Connell K.E., Gower S.T. & Norman J.M. 2003. Comparison of net primary production and light-use dynamics of two boreal black spruce forest communities. *Ecosystems* 6: 236-247.

Pachauri R.K., Allen M.R., Barros V.R., Broome J., Cramer W., Christ R., Church J.A., Clarke L., Dahe Q. & Dasgupta P. 2014. *Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change.* Geneva: IPCC.

Pan Y., Birdsey R.A., Fang J., Houghton R., Kauppi P.E., Kurz W.A., Phillips O.L., Shvidenko A., Lewis S.L. & Canadell J.G. 2011. A large and persistent carbon sink in the world’s forests. *Science* 333: 988-993.

Potter C.S., Klooster S. & Brooks V. 1999. Interannual variability in terrestrial net primary production: Exploration of trends and controls on regional to global scales. *Ecosystems* 2: 36-48.

Prince S. 1991. A model of regional primary production for use with coarse resolution satellite data. *Int. J. Remote Sens*. 12: 1313-1330.

Reese H., Nilsson M., Pahlén T.G., Hagner O., Joyce S., Tingelöf U., Egberth M. & Olsson H. 2003. Countrywide estimates of forest variables using satellite data and field data from the national forest inventory. *Ambio* 32: 542-548.

Running S., Mu Q. & Zhao M. 2015. *MOD17A2H MODIS/Terra Gross Primary Productivity 8-Day L4 Global 500m SIN Grid V006.* https://doi.org/10.5067/MODIS/MOD17A2H.006.

Smith B., Prentice I.C. & Sykes M.T. 2001. Representation of vegetation dynamics in the modelling of terrestrial ecosystems: comparing two contrasting approaches within European climate space. *Global Ecology and Biogeography* 10: 621-637.

Smith B., Warlind D., Arneth A., Hickler T., Leadley P., Siltberg J. & Zaehle S. 2014. Implications of incorporating N cycling and N limitations on primary production in an individual-based dynamic vegetation model. *Biogeosciences* 11: 2027-2054.

Ståhl G., Boström B., Lindkvist H., Lindroth A., Nilsson J. & Olsson M. 2003. Methodological options for quantifying changes in carbon pools in Swedish forests.

Tomppo E., Gschwantner T., Lawrence M., McRoberts R.E., Gabler K., Schadauer K., Vidal C., Lanz A., Ståhl G. & Cienciala E. 2010. National forest inventories. Pathways for Common Reporting. *European Science Foundation*: 541-553.

Tuomi M., Rasinmäki J., Repo A., Vanhala P. & Liski J. 2011. Soil carbon model Yasso07 graphical user interface. *Environmental Modelling & Software* 26: 1358-1362.

UNFCCC. 2013. *Report of the Conference of the Parties on its nineteenth session, held in Warsaw from 11 to 23 November 2013, Addendum Part two: Action taken by the Conference of the Parties at its nineteenth session*. FCCC/CP/2013/10/Add.3.

Vestin P. 2017. *Effects of forest management on greenhouse gas fluxes in a boreal forest*. Lund: Lund University, Faculty of Science, Department of Physical Geography and Ecosystem Science.

White M. A., Thornton P. E., Running S. W. & Nemani R. R., 2000. Parameterization and sensitivity analysis of the BIOME-BGC terrestrial ecosystem model: net primary production controls. *Earth interact.* 4: 1-85.

Zelli F. & Van Asselt H. 2013. Introduction: The institutional fragmentation of global environmental governance: Causes, consequences, and responses. *Global Environmental Politics* 13: 1-13.