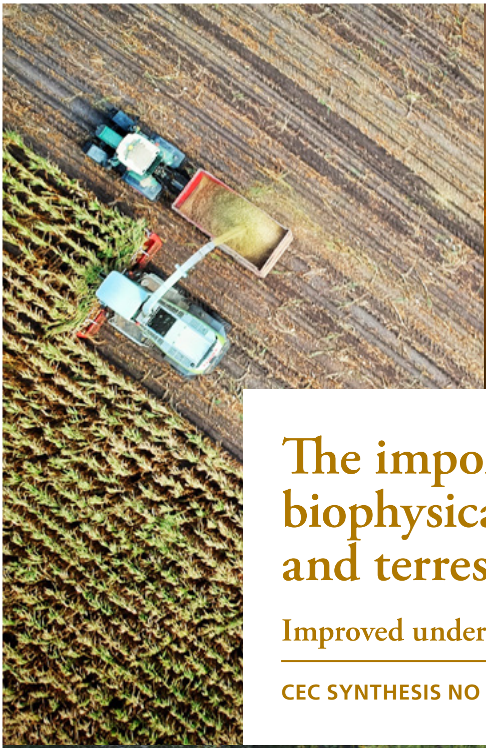

The importance of land-atmosphere biophysical interactions for regional climate and terrestrial ecosystem change

Improved understanding to inform Swedish national climate action

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Improved understanding to inform Swedish national climate action

Wilhelm May, Paul A. Miller and Benjamin Smith

CEC Synthesis No 05
Lund University 2020

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THE IMPORTANCE OF LAND-ATMOSPHERE BIOPHYSICAL INTERACTIONS FOR REGIONAL CLIMATE AND TERRESTRIAL ECOSYSTEM CHANGE: IMPROVED UNDERSTANDING TO INFORM SWEDISH NATIONAL CLIMATE ACTION

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Summary

Aim: The synthesis aims to lay the foundation for an improved understanding of the biophysical influence of land-use and land-cover changes (LULCC) on regional climate and terrestrial ecosystem change in Sweden, and to outline a roadmap for developing tools that support the formulation of policies and decision-making by policymakers, taking these potentially significant effects into account. The additional information and support tools will enable holistic assessments of the Swedish national climate policy for regional climate and terrestrial ecosystems.

Background: The Paris Agreement (PA) aims to cap global average temperature to well below 2 °C above pre-industrial levels, or 1.5 °C if possible. It is recognised that fulfilment of these goals will require mitigation solutions including land-based intervention. In accordance with the PA, the Swedish Government proposed the legal framework for a Swedish national climate policy. The new law came into force on January 1st, 2018. One aim of this pioneering policy is that Sweden should achieve zero net emissions of greenhouse gases by 2045; thereafter, negative emissions should be achieved. The national climate policy regards forestry as key for the necessary emission reductions in various sectors. Climate mitigation will therefore affect land use, including land management, and land cover in Sweden. However, assessments of the climate effects of the associated LULCC typically only consider the effects on the carbon budget, ignoring biophysical effects or other biogeochemical effects of LULCC.

Methods: Central to this synthesis is a review of the effects of LULCC on climate and terrestrial ecosystems based on the published scientific literature. Various biophysical and biogeochemical effects are considered, with a special focus on the climate conditions and vegetation zones of Sweden. Another essential component is an assessment of the modelling tools that are already available to researchers in Sweden. Some of them need to be advanced or extended to enable a comprehensive assessment of the effects of LULCC on climate and terrestrial ecosystems. A third component is an engagement with stakeholders, comprising representatives from various sectors and areas that most likely are affected by the national climate policy, i.e. forest industry, forestry and agriculture, natural resource management and nature conservation, and scientific stakeholders from Swedish universities and research institutions.

Results (1): The review of the scientific literature revealed marked effects of LULCC on climate and terrestrial ecosystems in Sweden, related both to biophysical and

biogeochemical interactions between the land surface and the atmosphere. In the case of re- and afforestation in Sweden, planting trees on open land will have both negative and positive effects on near-surface temperature due to opposing biophysical effects. The sign and magnitude of the balance of these effects is in general quite uncertain. Decrease in surface albedo will induce warming, while increased roughness length and increased evapotranspiration, especially in late spring and summer, cools the surface locally. Biogeochemical effects, i.e. increased carbon storage and increased atmospheric aerosol loading, are also cooling effects, but enacted on larger scales. In the long term, the efficacy of re- and afforestation as mitigation measure in Sweden will also be affected by the extent and patterns of future climate change in Sweden. Warmer near-surface temperatures, in particular in winter, and reduced precipitation during summer would counteract the cooling effects of afforestation.

Results (2): Several relevant modelling tools have been developed and used by Swedish researchers. These include the LPJ-GUESS terrestrial ecosystem model, the coupled land-atmosphere regional earth system model (ESM) RCA-GUESS, which couples the RCA regional climate model with LPJ-GUESS, and the global ESM EC-Earth, which also incorporates LPJ-GUESS to account for biophysical and biogeochemical feedbacks. Thus, Sweden has the foundational capacity and capability needed to overcome the limitations of the available modelling tools for assessing the biophysical (as well as biogeochemical effects) of LULCC.

Conclusions: Anthropogenic LULCC will play an important role for future climate, both because land use and land cover are affected by climate change and because adaptation and mitigation measures influence the land surface. Hence, future research needs to incorporate anthropogenic LULCC and its impacts on climate to the extent possible. This includes not only the physical, chemical and biological mechanisms operating in the earth system but also the socioeconomic processes affecting the human system and, thus, shaping societal changes through governance. The currently available ESMs do not explicitly include human behaviour and decision-making and, hence, miss the immediate feedbacks between the changes in land use, management and land cover and climate. While it is challenging to represent human decision-making and management in ESMs, it is a current research front with the goal to incorporate dynamic adaption or mitigation measures in response to the simulated climate changes. Recent work in which Swedish researchers are involved has started to address these limitations through coupling between and extensions to available models.

Recommendations: The synthesis makes a number of recommendations for future research, falling into four broad categories:

- Representation of processes: The theoretical understanding of several processes governing the interactions between terrestrial ecosystems and the atmosphere needs to be advanced. Modelling tools need to be extended to also include nutrient cycling and methane emissions as well as aerosol precursors such as biogenic volatile organic compounds. Disturbance processes need to be better represented in models. Processes governing the interactions between the land surface and the atmosphere in relation to climate variables other than temperature, i.e. precipitation and soil moisture, need to be evaluated and their representations in the models should be improved.

- Coupled model developments: Human decision-making should be incorporated in climate projections and the range of incorporated socioeconomic model components, e.g. sectors or policies, needs to be extended. To meet the specific requirements for Sweden, a new integrated RESM needs to be developed, coupling a physical climate model (including the essential ecological and physical processes) with a socioeconomic model that considers the sectors and policies that are important for the country.
- Land-use scenarios: Scenarios for land use and land cover that take into account the particular environmental, cultural and governance context of Sweden need to be developed, representing the effects of the Swedish national climate policy and its implementation on land use (including land management) and land cover. Available community scenarios for land use and land cover for Sweden need to be thoroughly validated against baseline land-cover data for Sweden, and additional regional details need to be added. Methodologies to upscale the local information (i.e. at landscape level) on LULCC to the scale of a climate model grid cell need to be developed.
- Relevance for national policies: A comprehensive assessment of the changes in land use and land cover due to adaptation and mitigation measures complying with the Swedish national climate policy is needed, considering both biogeochemical and biophysical effects. LULCC connected to the Swedish national climate policy need to be related to other national policies governing, for instance, biodiversity, water quality or food security. Interdisciplinary research is needed to identify and solve potential conflicts, and to maximize co-benefits, in relation to climate mitigation policies.

1. Introduction

The synthesis aims to lay the foundation for an improved understanding of the biophysical influence of land-use and land-cover changes (LULCC) on regional climate and terrestrial ecosystem change in Sweden, and to outline a roadmap for developing tools that support the formulation of policies and decision-making by policymakers, taking these potentially significant effects into account. The additional information and support tools will enable holistic assessments of the Swedish national climate policy for regional climate and terrestrial ecosystems.

The starting point of the synthesis is the need for climate mitigation to achieve the goals of the Swedish national climate policy. Mitigation measures will affect land use, including land management, and land cover. Assessments of the climate effects of the associated LULCC typically only consider the effects on the carbon budget, ignoring biophysical effects or other biogeochemical effects of LULCC. These effects, however, need also be considered to assess the effects of the national climate policy and its implementation on climate and terrestrial ecosystems in Sweden in a comprehensive way.

In the report, we have compiled the current scientific knowledge in relation to the aims of the synthesis and information on the modelling tools that need to be employed or to be advanced to provide a comprehensive assessment of the effects of LULCC, e.g. those employed to mitigate climate change, on both climate and terrestrial ecosystems in Sweden. In Chapter 2, the background of the synthesis is described, while the purpose of the synthesis is explained in Chapter 3. Chapter 4 introduces the methodology applied in the synthesis, i.e. review of the scientific literature (Chapter 4.1), engagement with stakeholders (Chapter 4.2) and modelling tools (Chapter 4.3).

In Chapter 5, the scientific research on the effects of LULCC on climate is surveyed, differentiating between the biophysical effects (Chapter 5.3), the biogeochemical effects (Chapter 5.4) and the combined biogeochemical and biophysical effects on climate (Chapter 5.5). We conclude this chapter by summarizing the overall effects of anthropogenic LULCC on climate in Sweden (Chapter 5.6). Chapter 6 introduces the Swedish national climate policy and describes the role that Swedish forests and forestry could play for climate mitigation, summarizing the scientific literature on this subject (Chapter 6.2). Chapter 7 summarizes the views of the stakeholders, i.e. stakeholders from several sectors affected by climate mitigation and from natural resource management (Chapter 7.1) and scientific stakeholders (Chapter 7.2). In Chapter 8, future scenarios of LULCC in Sweden are introduced, based on a selection of newly developed scenarios in accordance with the Shared socio-economic pathways (SSPs). Chapter 9 introduces several types of standard modelling tools for modelling the biophysical and biogeochemical effects of LULCC on climate (Chapter 9.2) and reports on ongoing research, where human decision-making is being incorporated into terrestrial ecosystem models or earth system models (ESMs; Chapter 9.3).

The report is completed by a discussion of the methodology that we have chosen to apply (Chapter 10), our main conclusions (Chapter 11) and, finally, a set of recommendations for future research to better represent the biophysical (as well as biogeochemical) effects of LULCC in modelling tools and to fully assess the effects of the Swedish national climate policy and its implementation on climate and terrestrial ecosystems in Sweden (Chapter 12).

2. Background

2.1 Climate change

In its fifth assessment report (AR5), the Intergovernmental Panel on Climate Change (IPCC) has summarized the evidence of observed changes in the climate system, described the drivers of climate change, and assessed potential future climate change at global and regional scales (IPCC 2013).

As for the observed changes, AR5 concludes that the "Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades and millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased." (IPCC 2013). A variety of substances and processes, both natural and anthropogenic, alter the Earth's energy budget. The radiative forcing (RF) quantifies the changes in the energy fluxes, with positive RF leading to a surface warming and negative radiative forcing to a cooling. A positive RF is associated with the well-mixed greenhouse gases (GHGs; i.e. carbon dioxide [CO_2], methane [CH_4], nitrous oxide [N_2O] and halocarbons) and a negative RF with most kinds of aerosols and with the albedo change associated with land use. In AR5 it is stated that "The radiative forcing is positive, and has led to an uptake of energy by the climate system. The largest contribution to total radiative forcing is caused by the increase in the atmospheric concentration of CO_2 since 1750."

Compared to the proceeding fourth assessment report, more detailed and longer observations as well as improved climate models have enabled the attribution of a human contribution to the detected changes in more components of the climate system in AR5: "Human influence on the climate system is clear. This is evident from the increasing greenhouse gas concentrations in the atmosphere, positive radiative forcing, observed warming, and understanding of the climate system."

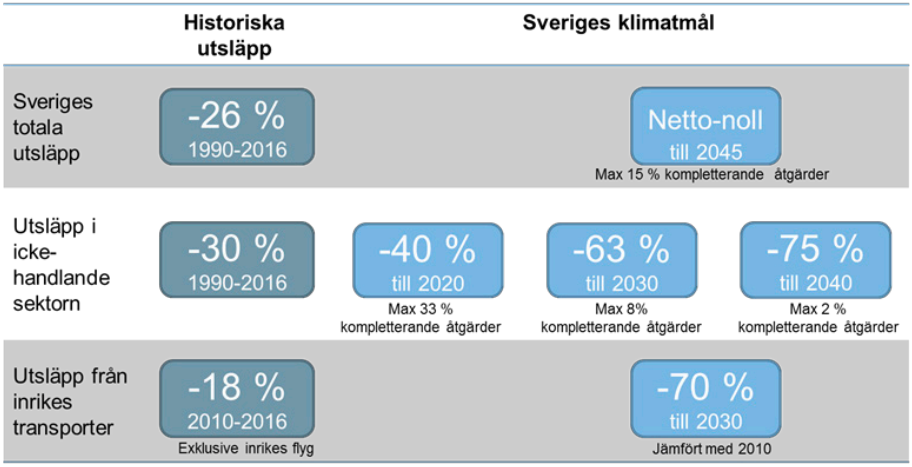
A hierarchy of climate models with different levels of complexity, including comprehensive climate models and ESMs have been employed to provide projections of future changes in the climate system. In AR5, a new set of scenarios was used, the representative concentration pathways (RCPs; e.g. Moss et al. 2010). In all four RCP scenarios, the atmospheric concentrations of CO_2 are higher by the end of the 21st century than at the beginning because of the continued emissions of CO_2 to the atmosphere during the century, only partly compensated by absorption by the ocean and terrestrial sinks. At the end of the 21st century, AR5 assumes atmospheric concentrations of 421 parts per million (ppm) CO_2 (RCP2.6), 538 ppm CO_2 (RCP4.5), 670 ppm CO_2 (RCP6.0) and 936 ppm CO_2 (RCP8.5), respectively, with a value of 391 ppm in 2011. When also the future changes in CH_4 and N_2O are considered as CO_2-equivalent (CO_2-eq), the corresponding values are grown to 475 ppm CO_2-eq (RCP2.6), 630 ppm CO_2-eq (RCP4.4), 800 ppm CO_2-eq (RCP6.0) and 1313 ppm CO_2-eq (RPP8.5), respectively. In conclusion, it is stated in AR5 that "Continued emissions of greenhouse gases will cause further warming and changes in all components of the climate system. Limiting climate change will require substantial and sustained reductions of greenhouse gas emissions." For the global mean temperature, it is concluded that "Global surface temperature change for the end of the 21st century is likely to exceed 1.5 °C relative to 1850 to 1900 for all RCP scenarios except RCP2.6. It is likely to exceed 2 °C for RCP6.0 and RCP8.5, and more likely than not to exceed 2 °C for RCP4.5. Warming will continue beyond 2100 under all RCP scenarios except RCP2.6."

2.2 Climate change mitigation

Limiting climate change requires a reduction of GHG emissions through climate change mitigation. Mitigation is defined as a human intervention to reduce the sources or enhance the sinks of GHGs (IPCC 2014b). Together with adaptation to climate change (e.g. IPCC 2014a), mitigation contributes to the objective of Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC), with the goal "to achieve stabilization of greenhouse gas concentrations in the atmosphere that would prevent dangerous anthropogenic interference with the climate system" (United Nations 1992). The convention further stipulates that "such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner".

In the recently adopted Paris Agreement (PA) under the UNFCCC, the long-term temperature goal has been set to "holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change" (United Nations 2015). In order to achieve this goal, the PA commits the participating countries to aim "to reach global peaking of greenhouse gas emissions as soon as possible" and "to undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century". Furthermore, the countries "should take action to conserve and enhance, as appropriate, sinks and reservoirs of greenhouse gases […], including forests".

In accordance with the PA and the Sustainable Development Goals (SDGs) of the United Nations, the Swedish Government proposed the legal framework for a Swedish national climate policy (Ett klimatpolitiskt ramverk för Sverige, Regeringens proposition 2016/17:146; Swedish Parliament 2017). The new law came into force on January 1st, 2018. The aim of this pioneering policy is that Sweden should achieve zero net emissions of GHGs by 2045; thereafter, negative emissions should be achieved. This is illustrated in Figure 2.1, where also intermediate goals for the emission reductions from sectors without emission trading (40% in until 2020, 63% until 2030 and 75% until 2040) and from transportation in Sweden (70% until 2030) are given. To combat climate change is one of the SDGs reflected in the Swedish national climate policy, including the aim to integrate climate measures into national policies, strategies and planning. The possibility of achieving several of the other SDGs is directly threatened by a changed climate, e.g. the goals to eradicate poverty and hunger, to secure access to water for all, to protect, restore and promote sustainable use of land-based ecosystems, to ensure sustainable energy for all, and to conserve and utilize the seas and marine resources.



	Historiska utsläpp	Sveriges klimatmål		
Sveriges totala utsläpp	-26 % 1990-2016	Netto-noll till 2045 Max 15 % kompletterande åtgärder		
Utsläpp i icke-handlande sektorn	-30 % 1990-2016	-40 % till 2020 Max 33 % kompletterande åtgärder	-63 % till 2030 Max 8% kompletterande åtgärder	-75 % till 2040 Max 2 % kompletterande åtgärder
Utsläpp från inrikes transporter	-18 % 2010-2016 Exklusive inrikes flyg	-70 % till 2030 Jämfört med 2010		

Fig. 2.1: Reductions of Sweden's historical greenhouse gas emissions since 1990 and in accordance to the goals of the Swedish national climate policy, distinguishing between the total emissions (upper row), emissions from sectors without emissions trading (middle row) and from transportation in Sweden (lower row). From Swedish Environmental Protection Agency (2018a)

According to the latest national inventory report for Sweden, the total greenhouse gas emissions in Sweden excluding land use, land-use change and forestry (LULUCF) amounted to 52.9 Megaton (Mt; a million tons) CO_2-eq in 2015 (Swedish Environmental Protection Agency 2018b). Figure 2.2 shows the Swedish GHG emissions, distinguishing between eight different sources, for the period 1990-2016.

Over that period the total Swedish GHG emissions have been reduced from about 95 Mt CO_2-eq in 1995 to about 53 Mt CO_2-eq in 2016. This means a reduction by 1.6% compared to 2015 and by 26% compared to 1990. The largest fraction of the GHG emissions come from the energy sector including transportation (37.8 Mt CO_2-eq in 2016; Swedish Environmental Protection Agency 2018b). In 2016 energy industries contributed to the emissions with approximately 9.2 Mt CO_2-eq (reduced by 8% compared to 1990) and transportation with about 16.9 Mt CO_2-eq (reduced by 12% compared to 1990). Industrial processes as well as agriculture (6.9 Mt CO_2-eq each) contributed with substantial GHG emissions, while waste (1.3 Mt CO_2-eq) gave a small fraction. The overall decrease in the GHG emissions of 26% compared to 1990 was mainly related to the strong reduction of the emissions from the energy sector by about 28% since 1990. LULUCF, on the other hand, has generated net uptakes of GHGs throughout the entire inventory period (since 1990), ranging between 32.6 Mt CO_2-eq in 1995 and 44.9 Mt CO_2-eq in 2015. In 2016, the net uptake was approximately 43 Mt CO_2-eq, meaning a slight reduction by about 0.4% compared to 2015 but a marked increase by about 20% compared to 1990.

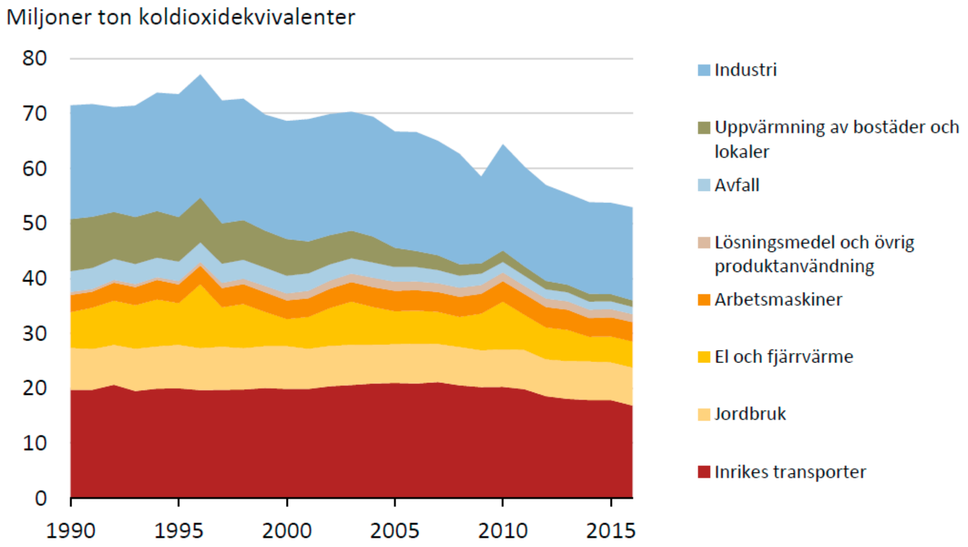


Fig. 2.2: Swedish greenhouse gas emissions for 1990-2016 from different sources. Units are Megaton CO_2-equivalent. From Swedish Environmental Protection Agency (2018a)

Land provides a variety of important ecosystem services that are vital for human health and wellbeing. These are the provision of food, energy and water, carbon storage, habitats for biodiversity, space for recreation and living as well as cultural services. At a global scale, 49 million (mio) km^2 of the global land area is currently used for agriculture and 40 mio km^2 is forested, equivalent to about 38% (agriculture) and 31% (forest) of the global land area. Under business as usual (BAU) scenarios for the future, the demand for land is projected to grow driven by economy and population growth (Benton et al. 2018). The energy demand, for instance, is projected to increase by 48% between 2012 and 2040, the water demand by 100% in 2100, and the demand for food by 60% in 2050. The latter is most likely associated with an expansion of cropland by 10-26%. On top of this, fulfilling the PA and, in particular, limiting the global warming to 1.5 °C will increase the demand on land for energy and carbon storage. Overall, the competition for land is expected to intensify in the future, driven by a number of policy decisions in the agriculture, forestry, energy and conservation sectors and other policies addressing, for instance, population growth or dietary preferences (e.g. Smith et al. 2010).

According to current emission scenarios, limiting the global warming to below 2 °C with a chance exceeding 50% will require large-scale deployment of negative emission techniques, resulting in the net removal of GHGs from the atmosphere. Smith et al. (2016) quantified the potential impacts (at a global scale) of such techniques on various aspects, i.e. land, GHG emissions, water, surface albedo, nutrients and energy, in order to determine the biophysical limits to their widespread application. The authors focused on several of the envisaged techniques, including bioenergy as well as afforestation and reforestation to sequester carbon in biomass and soils. Smith et al. (2016) based their study on recent modelling exercises, which showed that a median deployment of bioenergy with carbon capture and storage (BECCS) with negative emissions of around 3.3 Gigaton (Gt; a billion tons) C/year was needed to comply with the 2 °C-target. The authors estimated that a land area between 3.8 and 7 mio km^2 was needed to obtain the negative emissions of 3.3 Gt CO_2-eq/year in 2100. The land area needed to obtain negative emissions of 1.1 Gt CO_2-eq/year (mean) and 3.3 Gt CO_2-eq/year (maximum) through re- and afforestation was estimated at about 3.2 and 9.7 mio km^2, respectively, in 2100. These estimates may be compared to the overall area of about 50 mio km^2 of agricultural land in 2000. This means that the area required for BECCS to comply with the 2 °C target represents 7-25% of today's agricultural land. Similarly, the area for re- and afforestation is equivalent to 6-20% of the agricultural land. This range of land demands is 2 to 4 times larger than the land that is currently identified as abandoned and marginal (Canadell and Schulze 2014). Hence, using such large fractions of agricultural land to achieve net negative GHG emissions by means of bioenergy or via re- and afforestation will unavoidably reduce the land area available for food and other ecosystem services.

The fact that these demands may exceed the limited land area available brings up a number of questions, e.g. the extent to which technology can increase the capacity of land to deliver services, how land can be used in an optimal way or whether the land services will fall short of demand. These questions, in particular the question of the optimal use of land, were addressed in Benton et al (2018). It is, however, not clear whether it is possible to design a sustainable land-use strategy addressing the challenges embodied in both the PA and the SDGs of the United Nations. In order to do so, one would need to project the service delivery from the land under different land-use scenarios, aiming at balancing the limits and the sustainability of the provision, and map this onto demands. The authors found that developing a comprehensive, data based, approach to optimize land use to be problematic for several reasons. First, the same interventions may lead to different outcomes in different places and biological and ecological systems often respond unpredictable to interventions. Second, land management implies various kinds of trade-offs between services, among actors and between short-term and long-term costs and benefits. Third, the impacts of a given intervention are highly dependent on the context. This is because the impacts largely depend on the place where an intervention is adopted and the scale at which it is implemented. Thus, a range of factors can affect the outcome, including the geographical and temporal scale of the intervention's implementation.

2.3 Land-use and land-cover changes

The terms land-use change, and land-cover change are both used in the scientific literature, but they are not always used consistently. According to Pongratz et al. (2018), land cover is defined as the sum of all land surface properties at a given location, and it is typically described by vegetation and soil characteristics at that location. Land cover is often characterized by broad classes (e.g. forest, grassland or bare ground), which can be sub-divided into more detailed classes (e.g. deciduous forest, coniferous forest or mixed forest). Land use, on the other hand, relates to the purposes or functions that humans have assigned to a location and how humans interact with the land, and it is often characterized by broad classes (e.g. forestry, grazing or cropping). Land management refers to the land-use practices that are applied within these broad classes (e.g. sowing, fertilizing, harvesting, thinning or clear-cutting). Land-use change (LUC) then refers to either conversion among broad land-use classes (e.g. agricultural expansion) or shift in land management within these classes (e.g. agricultural intensification). Both kinds of LUC can result in land-cover change (LCC), either in a land-cover transition from one broad class to the other (e.g. forest loss) or in land-cover modifications, i.e. slight changes in ecosystem properties (e.g. forest degradation).

Anthropogenic LULCC have occurred during historic and modern times (e.g. Pielke et al. 2011, Mahmood et al. 2014). By 1500, large areas of western Europe had been partially cleared for agriculture and timber harvesting. LULCC intensified until 1800, particularly in western Europe, while significant LULCC also occurred over much of Asia, including India and China. By 1750, 6-7% of the global land surface area was under cultivation, and by 1990, 35-39% of the global land surface area was used as croplands or pasture. Large areas in the Southern Hemisphere underwent LULCC throughout the 20th century, and intensive LULCC impacted other areas such as the United States, western Europe, India and northern China. By 2000, only a few desert regions, the central Amazon and Congo Basins and the Arctic region had not been affected by LULCC. The large transition of forests to agriculture resulted in high CO_2 emissions during the period of anthropogenic LULCC (Ciais et al. 2013). Between 1750 and 2017 the cumulative CO_2 emissions from anthropogenic land-use change have been estimated at 235±95 Gt C, corresponding to about 35% of the total anthropogenic cumulative emissions of 660±95 Gt C over that period (Le Quéré et al. 2018). Although the emissions from land conversion have declined markedly in recent decades, this process still contributed with about 20% to the total anthropogenic cumulative emissions in the period 1959-2017, i.e. 80±40 of 350±20 Gt C.

2.4 Biophysical effects of land-use and land-cover changes on climate

LULCC have significant effects on climate, hydrology, water resources, soils, ecosystems and biodiversity through a spectrum of processes and interactions. In particular, LULCC affect climate at a variety of scales, ranging from local and regional to global scales through biophysical and biogeochemical interactions. The biogeochemical interactions are associated with the release or uptake of GHGs (primarily CO_2) and the emissions of black carbon and of organic carbon aerosols that can alter the atmospheric composition and consequently affect climate (e.g. Devaraju et al. 2015). The emissions of CO_2 have a global effect on climate, as locally emitted CO_2 is rapidly mixed throughout the global atmosphere and has a residence time of 100-300 years in the atmosphere. Effects of the aerosols are more local. The biogeochemical effect of LULCC on the carbon cycle is mainly related to differences in the carbon residence time and stocks stored in the ecosystems: the carbon stock in vegetation and soil, for instance, is larger for forests than grasslands or crops, due to the long-term storage of carbon in the growing stems of trees. Carbon turnover of soil can also vary substantially between different land-use types, with management interventions such as pre-plantation scarification in forestry, and tillage in agriculture, speeding the transfer of soil carbon to the atmosphere.

The biophysical effects of LULCC are related to the physical processes that depend on the characteristics of the land surface. Among the most important characteristics are albedo and roughness, the amount of green vegetation (e.g. leaf area index (LAI)) and plant physiology (e.g. leaf stomatal opening). The biophysical interactions influence the exchanges of shortwave and longwave radiation, the turbulent fluxes of sensible and latent heat (i.e. evapotranspiration) and momentum (e.g. Mahmood et al. 2014, Devaraju et al. 2015).

LULCC result in alterations of the albedo (the reflectivity of shortwave radiation at the land surface) and, hence, the surface energy balance. The albedo is generally lower for forests than for grassland and cropland (Bonan 2015). The albedo can be somewhat higher for bare soil and is much higher for snow. As a tall vegetation canopy can mask snow (with a higher albedo), the canopy cover is particularly important in boreal regions, where a large difference occurs when snow or herbaceous vegetation is masked by forest, particularly coniferous forest (e.g. Bathiany et al. 2010). As a result, afforestation in these regions could lead to a near-surface warming, and the effect on temperatures could differ substantially by season (Wramneby et al. 2010). Changes in evapotranspiration and roughness length may partially offset the warming (e.g. Betts 2000, Zhang et al. 2018).

Trees typically have a larger LAI and deeper roots than grasses, enabling them to transpire more water. Furthermore, because of the larger leaf area trees can often hold more water in the canopy than grasses after rainfall. Therefore, replacing forests with crops or grassland is generally associated with decreasing evapotranspiration. This effect is enhanced by the lower roughness length of non-forested vegetation (see below). In the case of an unaltered radiative budget at the surface, the reduced evapotranspiration leads to a near-surface warming because more energy is partitioned into sensible and less into latent heat flux (e.g. Bala et al. 2007). The reduced evapotranspiration can also affect the formation of clouds due to a drying of the atmospheric boundary layer (i.e. the lowest part of the atmosphere, which is directly influenced by its contact with the planetary surface; ABL), allow for increased downward solar radiation and, through this, leading to a surface warming.

LULCC also result in alterations of the roughness length (equivalent to the height above the ground where the wind speed theoretically becomes zero, assuming a logarithmic wind profile). The roughness length is much larger for tress than for grass or crops (Bonan 2015). The roughness length is a good indicator for the surface friction and turbulence in the ABL, which in turn effects the exchanges of momentum, heat and water vapour between the land surface and the atmosphere.

In addition to the land cover, changes in land use, including changes in land management, contribute to anthropogenic LULCC. In one of the first studies of its kind, Luyssaert et al. (2014) distinguished between the biophysical effects of land management changes and the biophysical effects of land-cover changes on near-surface temperatures at 22 temperate and two boreal sites in Europe and North America in the first decade of the century. They found that changes in land management and anthropogenic land-cover changes have impacts on near-surface temperatures of similar magnitude, with an estimated warming of 1.7 °C in the ABL at the sites considered. In the light of the large spatial extent of the areas subjected to land management (42-58% of the global land surface), changes in land management need to be considered when the human impact on climate is assessed.

2.5 Land-use and land-cover changes in relation to mitigation

The PA promotes forest management as a pathway towards ceasing climate warming through the reduction of CO_2 emissions. However, the climate-benefits from carbon sequestration may be reinforced, counteracted or even offset from the management-induced changes in surface albedo, land-surface roughness, emissions of biogenic volatile organic compounds (BVOC), transpiration and sensible heat flux. Luyssaert et al. (2018) investigated in further detail the trade-offs in using European forests to meet the climate objectives associated with the PA. A central premise of their study is that the agreement does not only require that forest management should reduce the growth rate of atmospheric CO_2 and the radiative imbalance at the top of the atmosphere. Two additional targets, the authors suggest, should be that the forest management neither increases the near-surface temperature nor decreases precipitation, because climatic changes arising from the changes in the terrestrial biosphere would make adaptation to climate change more demanding.

Luyssaert et al. (2018) analysed different forest management portfolios in Europe designed to maximize the carbon sink, maximize the forest albedo or reduce near-surface temperatures. They found that the portfolio maximizing the carbon sink complies with only one of the four objectives of the PA, i.e. reduces the growth rate of atmospheric CO_2. Similarly, the portfolio maximizing the forest albedo also satisfies only one of the four objectives, i.e. a slight reduction of the near-surface temperatures. The increase of the surface albedo that could be realized through this portfolio was compensated by a reduced cloud cover, so that this portfolio did not have any net effect on the radiative imbalance at the top of the atmosphere. The portfolio reducing near-surface temperatures, on the other hand, complies with two of the objectives, i.e. reduces the growth rate of atmospheric CO_2 in addition to a reduction of the near-surface temperatures. All three portfolios resulted in a reduction of annual mean precipitation.

For Europe as a whole, the portfolio maximizing the carbon sink is associated with an increase in the fraction of coniferous forest at the expense of deciduous forest compared to a portfolio sustaining the present-day management. The portfolio reducing near-surface temperatures, on the other hand, is linked to a decrease in the fraction of coniferous forest in favour of deciduous forest. In northern Europe, the latter corresponds to a considerable increase in the fraction of deciduous forest from 130,000 (BAU) to 480,000 km^2 while the portfolio maximizing the carbon sink is characterized by a much weaker increase to 190,000 km^2. In this case, the fraction of unmanaged forest is strongly increased from 79,000 (BAU) to 210,000 km^2 at the expense of high stand forest, which is reduced from 560,000 (BAU) to 370,000 km^2. For the portfolio reducing near-surface temperatures, on the other hand, much more forest is managed as coppice (290,000 km^2 vs. hardly anything for BAU), again at the expense of high stand forest, which is reduced to 260,000 km^2.

2.6 Modelling the effects of land-use and land-cover changes

ESMs allow to simulate the biogeochemical as well as the biophysical effects of anthropogenic LULCC on climate in a comprehensive and consistent way (e.g. Brovkin et al. 2013). These models incorporate components that simulate the biogeochemical cycles in the ocean and on land, including the dynamics of carbon stores in the oceans, soils and vegetation and the exchange of carbon with the atmosphere which, together with anthropogenic emissions, determine the atmospheric CO_2 concentration. The land surface is represented by a specific model component, which also include dynamical changes in natural vegetation. Anthropogenic LULCC are prescribed in these land surface models by specifying the land cover (e.g. forests or grasslands) and land use (e.g. croplands or pastures). In some cases, wood harvest or transitions between different kinds of land use are considered as well. In Brovkin et al. (2013), data from specifically designed simulations with 6 ESMs were analysed in order to assess the effect of anthropogenic LULCC on climate and on the land carbon storage during the 21st century. Two sets of simulations for the period 2006-2100 were run for two RCP scenarios (i.e. RCP2.6 and RCP8.5), with the land use prescribed in accordance with these scenarios (Hurtt et al. 2011) in one set of simulations and with the land use prescribed to the state in 2006 in the other. In these simulations, the concentrations of atmospheric CO_2 (as well as other GHGs) were prescribed from corresponding simulations without LULCC but forced with anthropogenic emissions of CO_2.

Deforestation and afforestation are particular aspects of anthropogenic land-cover changes, which have received considerable scientific attention over the last two decades (e.g. Perugini et al. 2017). Deforestation has and is still taking place at large scales, while afforestation (together with forest management) is considered as one of the key instruments for climate mitigation. Often, the simulations addressing deforestation and/or afforestation are idealized in that the changes in forest cover are prescribed in different climate zones, i.e. the tropics or the boreal zones. According to Bathiany et al. (2010), for instance, complete deforestation in the tropics leads to a global warming of 0.4 °C due to an increase in the atmospheric CO_2 concentration and a decrease of evapotranspiration in the deforested areas. In the northern mid- and high latitudes, complete deforestation leads to a global cooling of 0.25 °C, while complete afforestation leads to an equally strong global warming, despite the counteracting changes of the CO_2 concentration, i.e. an increase in the case of deforestation and a decrease for afforestation. Deveraju et al. (2015) confirmed the opposing effects of complete deforestation in the tropics leading to a global warming and in the boreal zones causing a global cooling. Separating between the biogeochemical and the biophysical effects indicated that the warming associated with the tropical deforestation is mainly caused by biogeochemical effects, while the cooling associated with the boreal deforestation is primarily due to biophysical effects, in particular the increased albedo associated with the reduced masking of the snow cover in winter.

2.7 Uncertainties related to land-use and land-cover changes

Climate simulations performed with different comprehensive climate models are characterized by some variations, typically owing the representation of certain physical processes in these models (e.g. Flato et al. 2013). As a consequence, different climate models also give a range of future climate projections for a given forcing scenario. Moreover, given the wide range of possibilities for how humankind might respond to the threat of climate change through changes in technology, economies, lifestyle and policy, a wide range of different forcing scenarios is possible (e.g. Moss et al. 2010). As for the RCPs, four different forcing scenarios have been derived, reaching different magnitudes of the radiative forcing, i.e. RCP2.6 (peaking at about 3 W/m^2 before 2100 and then declining until 2100), RCP4.5 (stabilizing at about 4.5 W/m^2 after 2100), RCP6.0 (stabilizing at 6.0 W/m^2 after 2100) and RCP8.5 (exceeding 8.5 W/m^2 by 2100).

The four RCP scenarios have been obtained using four different integrated assessment models (IAMs). As these models use different approaches for modelling land use, the characterisations of anthropogenic LULCC can differ considerably between different IAMs. Similarly, the characterizations of anthropogenic LULCC vary between different ESMs due to differences in the respective land surface models. In order to overcome these differences, Hurtt et al. (2011) produced harmonized land-use scenarios for the period 1500-2100, distinguishing between the four RCP scenarios after 2005. They provided consistent time series of land-use states (fractions of each land-use category in a grid cell) and transitions (changes between land-use categories in a grid cell) for this period, referred to as the LUH data. The cropland, pasture, and wood harvest projections originating from the four IAMs were smoothly connected to the historical reconstruction of agricultural land use from the History Database of the Global Environment (Klein Goldewejk et al. 2011). This approach, however, gives rise to three sources of uncertainty (Prestele et al. 2017). First, the LUH data evolves from one particular data set for the historical period. Second, there are large inconsistencies between the present-day estimates of land use. Finally, the future projections in the LUH data originate from four different IAMs with structural differences in the way they incorporate LULCC.

3. Purpose of the synthesis

3.1 Motivation

As described in Chapter 2.2, climate change mitigation is important to achieve the goals of the PA and will require marked changes in land use and land cover. This is also reflected in the Swedish national climate policy, which highlights the importance of using more sustainably produced bioenergy from forestry to achieve the necessary emission reductions in various sectors in Sweden, e.g. industry, construction, energy and transportation. The aim of the policy is that Sweden should not have any net emissions of GHGs by 2045 at the latest. Thereafter, negative emissions should be achieved. In order to reach this aim, forest management might have to be intensified and forested areas to be extended to marginal land and to areas, which now are used as pastures or croplands. All these actions will lead to distinct LULCC at a local or landscape level.

At present, the considerations of LULCC for climate change mitigation are based on their impact on land carbon storage and on their contributions to avoiding carbon emissions from fossil fuels. This means that they are based only on the biogeochemical interactions (i.e. carbon sequestration) of LULCC with climate. As described in Chapters 2.4 and 2.5, LULCC can also have considerable impacts on the regional climate through profound biophysical effects that reinforce, counteract or even offset the climate-benefits from carbon sequestration. Current policy instruments, however, target the reduction of GHG emissions rather than mitigation of climate change per se. Only when the biophysical effects of LULCC associated with measures to avoid GHG emissions are considered as well, the overall effects of these measures on climate mitigation can be assessed. Such a comprehensive evaluation of mitigation measures is needed as the basis of well-informed decisions when implementing the Swedish national climate policy.

3.2 Aims and objectives

The overall aims of the synthesis are to lay the foundation for an improved understanding of the biophysical effects of LULCC for regional climate and terrestrial ecosystem change in Sweden and to outline a roadmap for developing tools that support the formulation of policies and decision-making by policymakers, accounting for these effects. These efforts should be targeted to the specific environmental conditions and the social, cultural and business context of Sweden. The additional information and support tools are prerequisites to assessing the implications of the national climate policy for regional climate and terrestrial ecosystems, including their effects on water resources, soils, land productivity and biodiversity.

The synthesis follows a number of objectives in order to fulfil these overall aims, namely:

- to summarize the current scientific knowledge on the biophysical effects of LULCC on climate and terrestrial ecosystems and on the inherent uncertainties regarding the sign, the magnitude and the seasonality of these effects, particularly in the Swedish context,
- to chart the views that stakeholders from the most relevant sectors (i.e. forestry, agriculture, nature conservation) have on the goals of the national climate policy and on ways for LULCC-related interventions to contribute to the implementation of the policy, generally and with relevance for their specific sector,
- to evaluate LULCC scenarios associated with the shared socioeconomic pathways for Sweden in the light of the situation on the ground in Sweden and in the context of the national climate policy,
- to provide an overview of the most relevant available modelling tools and frameworks with the potential to be applied and extended to enable the assessment and quantification of the efficacy of LULCC-related interventions including both biogeochemical and biophysical effects, and
- to chart the development of national capacity and capability needed to extend the utility and to overcome the limitations of available modelling tools.

3.3 Outcome

The main outcome of the synthesis is to stake out the way for an enhanced capability to undertake comprehensive assessments of the effects that LULCC associated with the present and future national climate policies for Sweden have on climate and terrestrial ecosystems. Such a comprehensive assessment requires not only an improved understanding of the biogeochemical and biophysical interactions between LULCC and climate, but also more advanced modelling tools. In addition to improved representations of the processes governing these interactions, the modelling tools need to incorporate functionality to address the key questions and interests of the relevant stakeholders with respect to the national climate policy and to other factors in their decision-making, e.g. the market prices for bioenergy crops and forest products. At present, no single modelling tool is available to enable an integrated evaluation across sectors and between climate and the terrestrial ecosystems with which it interacts as a feedback system, and further research is therefore needed. To capitalise on past investment in research, any such system should build further on one or more existing and well proven frameworks, if indeed these can be engineered to address a wider range of relevant questions, by combining (coupling) or building further on the existing frameworks. A further key consideration is how to integrate the responses of the relevant sectors in the modelling tool by allowing for stakeholders' questions or "scenarios" to be specified as part of the input. Finally, a "workflow" needs to be developed to translate raw output from model "experiments" into answers expressed in the language or metrics used by managers and policymakers to inform national climate policy, also accounting for the uncertainties related to stakeholders' decision-making processes. This synthesis gives recommendations for future research and development targeting the provision of such a comprehensive modelling tool for the particular context of Sweden.

The synthesis as a whole is documented in this report. Based on the report, a manuscript for publication in an international scientific journal is being prepared, describing the background for and presenting the findings of the synthesis, combined with recommendations for future research. The finalization of the synthesis report is accompanied by a press release. The report is accompanied by some electronic supplementary material (see below).

4. Methodology of the synthesis

4.1 Review of the scientific literature

Chapter 2, where the background of the synthesis is described, already includes several references to recent scientific articles related to the subject of the synthesis, i.e. the importance of the biophysical effects of LULCC for regional climate and terrestrial ecosystem change in Sweden. As a part of the synthesis, a more thorough review of the scientific literature addressing specific questions has been undertaken. Furthermore, all scientific papers scrutinized while working on the synthesis are added as electronic material, along with a categorization of these articles.

Moreover, a mapping of the scientific literature has been undertaken, distinguishing between different aspects, i.e. land use, land cover or forest, biophysical effect, temperature and precipitation, future climate, Europe, etc. In their systematic quantitative review, Perugini et al. (2017) analysed scientific articles on the biophysical effects on temperature and precipitation due to land cover change. The authors analysed a total of 126 scientific articles (published after January 2000) and ended up with 28 articles which fulfilled their selection criteria. That is, each of these 28 studies reported variations in near-surface temperatures and/or precipitation caused by an explicit land-cover transition, considered annual averages of these climate variables, reported the effects at a regional and/or global level, and reported only variations of these climate variables related to biophysical factors. The literature review presented here goes beyond the review by Perugini et al (2017) in several aspects. We will consider both the biophysical and biogeochemical effects on climate as well as effects on terrestrial ecosystems, including several recent studies based on observations. We will have a particular focus on the mid-latitudes of the Northern Hemisphere and the boreal zone, where Swedish ecosystems are placed. In addition, we will review the current state of modelling the biophysical effects of LULCC, reaching from land surface models (some of them incorporating dynamic vegetation models) and IAMs to global and regional ESMs (RESMs).

4.2 Engagement with stakeholders

The interaction with relevant stakeholders is an important part of the synthesis. The communication with stakeholders from forestry, agriculture and nature conservation, the most important sectors in relation to land use, provides us with information on the current thinking as to possible future pathways of LULCC in Sweden in the context of the national climate policy and global socioeconomic trends. Moreover, these stakeholders can identify current knowledge gaps and the related sources of uncertainty, which may affect their decisions. The contact with policymakers that are responsible for the Swedish climate policy was valuable to identify their need for information to assess the effects of the present and future climate policies, considering the biophysical effects on climate or terrestrial ecosystems as well. The exchange with Swedish experts with applicable model experience was essential for charting the future model development, which is needed to be able to provide comprehensive assessments of the impacts of national climate policies, incorporating the biogeochemical and biophysical effects of LULCC as well as the stakeholders' decisions on how to respond to the policies. The interaction with the stakeholders was facilitated through a specific workshop (relevant sectors and policymakers) and discussions within the strategic research area on "Modelling the Regional and Global Earth System" (MERGE; see http://www.merge.lu.se) for the modelling experts.

4.3 Modelling tools

In order to assess the biophysical (as well as the biogeochemical) impacts of LULCC on regional climate and terrestrial ecosystems suitable modelling tools are essential. In the synthesis, we identify two specific state-of-the-art modelling tools, i.e. the LPJ-GUESS dynamic global vegetation model (DGVM) and the RCA-GUESS RESM, as leading examples of their kind. These modelling tools have been primarily developed in Sweden, and Swedish researchers have rich experience with using these tools. Given the national capability and capacity with these modelling tools, it seems to be natural to capitalize on the investments in the underlying development and research and to build on this well-proven framework. Together with the Swedish contribution to the EC-Earth consortium (see Chapter 7.2), LPJ-GUESS and RCA-GUESS build on the collaboration in the MERGE strategic research area, bringing together researchers from five Swedish universities (see Chapter 7.1) and the Swedish Meteorological and Hydrological Institute (SMHI).

Dynamic global vegetation model

Various aspects of vegetation are simulated by the LPJ-GUESS DGVM (e.g. Smith et al. 2001, 2014). LPJ-GUESS was one of the first second-generation DGVMs (e.g. Fisher et al. 2010), in which the dynamics of ecosystems arise from neighbourhood-scale interactions between cohorts (characterized by age and size) of different plant functional types (PFTs; classifications of plants according to their physical, phylogenetic and phenological characteristics). Incorporating size structure and demography of vegetation and explicitly accounting for competitive interactions of growing vegetation stands are recognized as important for the accurate simulation of ecosystem carbon balance, its response to climate, and recovery following land-use change, management interventions such as forest harvest, and natural disturbances such as wildfires (Fisher et al. 2010; Pugh et al. 2019). First-generation DGVMs, which are included in the majority of current global ESMs, incorporate simplified area-based representations of vegetation dynamics, with negative implications for accuracy and extensibility (Purves and Pacala 2008). However, many of the international climate modelling centres developing updated ESM versions for the Coupled Model Intercomparison Project Phase 6 (CMIP6; Eyring et al. 2016) are incorporating new demography-based schemes for vegetation dynamics, similar to the approach of LPJ-GUESS (Fisher et al. 2018).

In LPJ-GUESS, the competition for light, water, space and nutrients not only takes place between various tree, shrub and grass PFTs but also between cohorts of PFTs. Cohort individuals grow (i.e. increase their biomass and, for woody PFTs, their height and stem diameter) by allocating their yearly net primary production (NPP) to their plant components (leaves, roots and stems) following a set of PFT-specific allometric relationships. The phenology of roots and leaves differs across PFTs, and is simulated daily. The main components of an individual's NPP are autotrophic respiration and photosynthesis, both simulated daily, the latter conjointly with stomatal conductance in a dedicated sub-model (Smith et al. 2001, 2014).

These processes are simulated in a number of replicate patches in each model grid cell, thereby capturing the variation in a landscape resulting from different trajectories of population dynamics (i.e. establishment and mortality) and disturbance, simulated by stochastic processes in the model, but influenced by the demography, resource status and climate forcing. Applied at a global scale LPJ-GUESS distinguishes, for instance, between 11 PFTs, i.e. three types of boreal trees (boreal needleleaved evergreen, boreal shade-intolerant needleleaved evergreen and boreal needleleaved summergreen tree), three types of temperate trees (temperate broadleaved summergreen, temperate shade-intolerant broadleaved summergreen and temperate broadleaved evergreen tree), three types of tropical trees (tropical broadleaved evergreen tree, tropical shade-intolerant broadleaved evergreen and tropical broadleaved raingreen tree) and two types of grasses (C3 [cold] and C4 [warm] grass) (Smith et al. 2014). Alternatively, different tree species can be presented in LP-GUESS rather than different PFTs (Hickler et al. 2012).

LPJ-GUESS also includes plant and soil dynamics of nitrogen (N) and carbon (C) and N-C interactions for both natural vegetation (Smith et al. 2014, Wårlind et al. 2014) and crops (Olin et al. 2015a). N controls plant productivity due to its limited availability and affects the carbon storage in terrestrial ecosystems. LPJ-GUESS incorporates stochastic disturbances, related to human influences (e.g. clear-cutting) or natural disturbances (e.g. wild fires), removing all vegetation (Smith et al. 2001). LPJ-GUESS includes a specific module for simulating terrestrial ecosystems at high latitudes (e.g. Zhang et al. 2013). This module includes additional PFTs and cold-climate processes representing the characteristic vegetation at high latitudes (i.e. tall, low and prostrate shrubs, lichens and moss) and explicitly describes permafrost and peatland processes, including the exchange of CO_2 and CH_4. LPJ-GUESS needs to be forced by daily information on the local climate conditions developing through time, i.e. the near-surface temperatures, humidity and wind speed as well as precipitation and incoming shortwave radiation. In addition, the atmospheric CO_2 concentrations needs to be prescribed to the ecosystem model.

Lindeskog et al. (2013) integrated cropland and pastures and their management as well as vegetation recovery and succession following cropland abandonment into LPJ-GUESS. This means that LPJ-GUESS fully accounts for both land management and LULCC. Cropland is represented by 11 crop functional types (CFTs), i.e. temperate cereals, rapeseed, maize, pulses, sugar beet, rice, soybean, sunflower, tropical cereals, peanut and cassava. Croplands are harvested each year and the two grass PFTs (C3 and C4 grass) are used as cover crops between harvest and sowing, and the same two PFTs are used to represent pastures. When converting from forest to cropland, 70% of the tree stems are assumed to be harvested and the rest is burned in the same year. At cropland abandonment (transition to natural vegetation) a new stand is created from bare ground but retaining the history of C and N in the soil from the cropland. This allows for the successive establishment of natural vegetation, e.g. from grass to deciduous or evergreen trees, depending on the location. Olin et al. (2015a, b) applied this version of LPJ-GUESS to investigate the impacts of changes in the atmospheric CO_2 concentration and N management on wheat yields in western Europe and the implications of different practices of managing soil carbon on crop yields and N leaching in the tropics and the temperate zone of the Northern Hemisphere, respectively.

In any modelled grid cell, LPJ-GUESS simulates the dynamic, climate-determined structure, composition and functioning of separate stands representing natural vegetation, pasture, cropland, managed forest and wetlands. The fraction of the grid cell covered by each stand type can change in time, following external LULCC datasets (e.g. LUH2, Hurtt et al. 2011; see Chapter 8.2). State variables for each stand type are output daily, monthly and annually as required, and include the most important structural, compositional and biogeochemical variables and fluxes needed to understand changes to the form and function of ecosystems in response to global environmental change. These include variables describing the vegetation state (PFT or species composition, LAI, vegetation height, biomass, tree and shrub density, burnt area), those relating to the state and functioning of the soil (water content, C and N content, temperature, runoff, N leaching, loss of dissolved organic C and N), and climatically important fluxes to and from each stand (evapotranspiration, gross and net primary productivity, autotrophic and heterotrophic respiration, fluxes from wildfires, CH_4 and N trace gases, isoprene and monoterpene, and net ecosystem exchange [e.g. Keenan and Williams 2018]).

Modelling terrestrial ecosystems in Sweden

LPJ-GUESS has been applied in many studies to simulate terrestrial ecosystems in Sweden, Fennoscandia or Europe, under current, future as well as historic and pre-industrial climate conditions. The first example of such a study was Koca et al. (2006), investigating the impacts of climate change on natural ecosystems in Sweden associated with different regional climate change scenarios. The results showed that all the different climate scenarios considered were associated with an extension of the boreal forest treeline with respect to latitude and altitude by the end of the 21st century. In the boreal and boreo-nemoral zones, the dominance of Norway spruce and to a lesser extent Scots pine was found to be reduced in favour of deciduous broadleaf tree species. Miller et al. (2008) used LPJ-GUESS to simulate the effects of climate and biotic drivers on Holocene vegetation at two locations in Sweden and two locations in Finland. The results indicated, for instance, that the observed northern distribution limits of temperate trees as well as the limits of Scots pine and Grey alder at the tree line were a result of millennial variations in summer and winter temperatures. Smith et al. (2008) applied LPJ-GUESS to demonstrate the potential for dynamic vegetation modelling constrained by satellite data to monitor the carbon balance of boreal conifer forest in northern Europe. The authors found that such a combination represents a promising step towards the development of operational tools for monitoring forest carbon balances at large scale. When using common European tree species instead of PFTs in LPJ-GUESS, Hickler et al. (2012) noticed a general improvement of the simulated natural vegetation in Europe than for a suitable selection of PFTs. Although the authors identified substantial discrepancies with the actual distribution of tree species at fine scales, the revision of LPJ-GUESS represented a considerable advance in modelling dynamic changes in natural vegetation across Europe. Scenario simulations performed with this version of LPJ-GUESS indicated the possibility of substantial changes in natural vegetation across Europe in response to future climate change.

Jönsson et al. (2015) used a version of LPJ-GUESS extended to include various processes of particular relevance to forests, i.e. forest management, storm damages, spruce bark beetle attacks and forest economy. The goal of the study was to evaluate the effect of four different options for forest management in Sweden, i.e. default forest management, shorter rotation period, increased fraction of broadleaf trees and continuous cover forestry, on forest growth in Sweden during the 21st century. The simulations with the LPJ-GUESS ecosystem model, driven by a specific future climate scenario, showed that a management strategy implemented by a majority of the forest owners could have a large-scale effect on the standing volume and the risk, e.g. the risk of storm damage. In order to reduce the risk of storm damages and to reach the desired management goals, a portfolio of adaptation strategies is needed. Lagergren and Jönsson (2017) used the same version of the LPJ-GUESS ecosystem model to investigate how to combine forest management strategies at a landscape level to optimize the provision of ecosystem services by the forest in various parts of Sweden with different bioclimatic conditions, i.e. northern boreal, southern boreal and nemoral conditions. The ecosystem services wood production, carbon sequestration and biodiversity were considered. The overall finding of the study was that combinations of forest management strategies (e.g. even-aged forestry with particular tree species and thinning regimes, continuous cover forestry with particular management types or unmanaged forest) could lead to a better fulfilment of various management goals at a landscape level than the current forest management practices.

Regional earth system model

In order to characterise the biophysical feedbacks of climate-induced vegetation shifts, LPJ-GUESS has been interactively coupled with the RCA regional climate model (RCM; e.g. Samuelsson et al. 2011). The resulting coupled model system is referred to as RCA-GUESS (Smith et al. 2011). In RCA-GUESS, vegetation dynamics and leaf phenology simulated by LPJ-GUESS in response to the climate information from RCA influence climate by affecting the relative cover and type of forest and open land, which are the two vegetated fractions (tiles) for each grid cell in the land surface scheme of RCA. The specific forest types simulated by LPJ-GUESS are aggregated into needleleaf and broadleaf trees before providing the information to RCA, while open land includes a varying coverage of herbaceous vegetation. The relative fraction of different vegetation types affects the surface albedo in a grid cell of the model, which is a weighted average of the prescribed albedo constants for needleleaf and broadleaf trees, open land vegetation, snow and bare soil. Similarly, the fluxes of energy at the land surface in a grid cell, i.e. fluxes of sensible and latent heat, are the weighted averages from the individual tiles. The surface energy fluxes in each tile are affected by the LAI, surface roughness and stomatal conductance of the particular type of vegetation in the tile. As input data, LPJ-GUESS receives daily mean temperature, precipitation and incoming shortwave radiation from RCA as well as the atmospheric concentration of CO_2. The latter affects plant photosynthesis and stomatal regulation through biochemical and hydrological mechanisms (e.g. Smith et al. 2001). Emissions of CO_2 and CH_4 from the vegetation are simulated by LPJ-GUESS, enabling biogeochemical ecosystem responses to be assessed consistently with the biophysical feedbacks. However, as RCA-GUESS is always applied over a limited regional domain, the biophysical feedback loop is closed but the biogeochemical feedback loop is not. This is because GHG emissions are rapidly mixed in the global atmosphere and, therefore, it would not be valid to adjust the atmospheric concentrations of these GHGs over the limited domain covered by RCA.

Smith et al. (2011) applied RCA-GUESS to simulate the climate of the recent past (1961-1990) and for a climate change experiment until the end of 21st century (1991-2100) over Europe. It was found that RCA-GUESS simulates the climate of the recent past with a similar accuracy as the standard RCM. Large-scale patterns of LAI, NPP and the composition of vegetation were consistent with observations, although during winter the LAI was systematically overestimated in RCA-GUESS. Both the simulation for the recent past and the climate change experiment revealed pronounced covariations between various variables describing aspects of climate and vegetation, respectively. At a Mediterranean site in south-eastern Spain, for instance, periodic soil water limitations led to fluctuations of leaf cover and a positive feedback with near-surface temperature. At an alpine site in northern Sweden, rising temperatures led to the advance of trees onto treeless tundra areas, reducing the surface albedo and resulting in a positive feedback with temperature. Although still apparent, the coupling between vegetation and climate was less pronounced at temperate and boreal sites.

Wramneby et al. (2010) used RCA-GUESS to identify hot spots of (biophysical) vegetation-climate feedbacks for future climate conditions in Europe. In order to do so, two separate simulations were performed over Europe for 1961-2100, one with and one without feedbacks from the vegetation dynamics enabled. In the "feedback" simulation, RCA and LPJ-GUESS were coupled throughout the entire simulation period. In the "non-feedback" simulation for 1991-2100, on the other hand, RCA was not coupled with LPJ-GUESS. Instead, the state of the vegetation was prescribed as obtained from the long-term daily means from the coupled simulation for 1961-1990. The difference between the future climate changes (2071-2100 vs. 1961-1990) from the feedback simulation and the corresponding future climate changes from the non-feedback simulation then indicates the contributions of the vegetation-climate feedback to the respective climate changes. Three potential hot-spots of this feedback could be identified in Europe. In the Scandinavian mountains, reduced albedo resulting from the snow-masking effect of forest expansion enhanced the winter warming trend (positive feedback). In central Europe, the stimulation of photosynthesis and plant growth caused by the increased CO_2 concentration mitigated the future warming by a negative feedback through enhanced evapotranspiration associated with the increased vegetation cover and LAI. In southern Europe, increased summer dryness restricted plant growth and survival, leading to a positive feedback through reduced evapotranspiration. Overall, the contributions of the vegetation-climate feedbacks over Europe were found to be rather modest as compared to the rather strong radiative forcing caused by the projected anthropogenic increase in the atmospheric GHG concentrations, although they modified the future warming trends regionally and seasonally.

Zhang et al. (2014b) applied RCA-GUESS over the Arctic region (including the northern part of Sweden), focusing on the role of the biophysical feedbacks of vegetation on the terrestrial uptake of carbon in the Arctic. They used the same experimental design as Wramneby et al. (2010), performing one scenario simulation with and one without biophysical feedbacks from natural vegetation. It was found that regardless of the biophysical feedback the terrestrial ecosystems in the Arctic continue to sequester carbon under a changing climate, with an increased uptake until the 2070s and a weaker uptake thereafter. The overall increase of atmospheric CO_2 and the associated future warming resulted in an encroachment of trees onto tundra during the 21st century and greater productivity in existing forests. The authors identified two opposing biophysical feedback mechanisms of the vegetation that modulate this response to the increased anthropogenic climate forcing regionally and seasonally. The albedo feedback dominates in winter and spring, amplifying the near-surface warming considerably (positive feedback). In summer, the evapotranspiration feedback prevails, leading to a distinct cooling. These feedbacks stimulate vegetation growth, as the growing season starts earlier, leading to compositional changes in woody plants and a redistribution of vegetation. Zhang et al. (2018) used LPJ-GUESS to further investigate the role of the biophysical feedbacks of vegetation in the Arctic region under climate scenarios with different climate forcing. The authors found that two biophysical effects have the potential to alter future climate change in the Arctic region, i.e. an albedo-mediated warming in early spring and an evapotranspiration-mediated cooling in summer, amplifying or modulating local warming and enhancing summer precipitation over land.

RCA-GUESS has also been applied to study tropical and subtropical regions of Africa and South America. Wu et al. (2016) studied the vegetation-climate feedbacks in Africa, focusing on their impact on rainfall patterns under future climate change. They found that the increased atmospheric CO_2 concentration in combination with the projected climate changes brought about increased tree cover and LAI, particularly over the subtropical savannah areas. These changes in natural vegetation affected the regional climate by altering surface energy fluxes. However, they also resulted in remote effects over central Africa by altering the large-scale atmospheric circulation, leading to a redistribution of precipitation in the region. For South America, Wu et al. (2017) investigated the biophysical and biogeochemical impacts of LULCC on climate and terrestrial ecosystem productivity, with a special focus on Amazonia. In one simulation with RCA-GUESS, the natural vegetation was not disturbed by any human activity. In a second simulation, historical land-use changes (mainly deforestation) according to the LUH data (Hurtt et al. 2011) were introduced. The differences between the two simulations indicated that the imposed LULCC had local and remote effects on climate in South America, i.e. significant local warming in the deforested areas, changes in the circulation pattern over Amazonia during the dry season, and a predominantly intensified hydrological cycle during the wet season in the areas affected by LULCC. These two studies clearly illustrate the strong role that biophysical feedbacks can have for regional climate, in these cases in relation to future changes in natural vegetation due to global warming in central Africa or in relation to historic land-use changes in South America.

5. Research on the effects of land-use and land-cover changes on climate

5.1 Mapping the scientific literature

In order to get an overview of the scientific literature on the biophysical effects of land use, land cover and forest as well as their changes, we have searched in two different databases to map the scientific literature relevant to the subject of this synthesis. These are the Web of Science (WoS; http://www.webofknowledge.com) and the Google Scholar databases (GS; http://scholar.google.com), respectively. Only scientific articles for the period 2000-2018 have been considered.

Table 5.1 gives the different categories that we have used when searching in the WoS database and their definitions. The main categories distinguish the state of the land (land use, land cover and forest cover), the biophysical effects, climate variables, observations and models, future climate and Europe. Furthermore, studies dealing with geological time scales have been excluded. These categories have been combined (see Table 5.2) to narrow the search and end up with a manageable final list of relevant scientific articles. A state of the land search alone, yields several hundred thousand articles, with some overlaps (see Table 5.2). The majority of the articles are on forest cover (246,000), less on land use (116,000) and considerably less on land cover (44,000). The inclusion of biophysical effects significantly reduces the number of articles, in particular for the forest cover by a factor of 200 and less for land use (factor of 90) and land cover (factor of 70), respectively.

Table 5.1: Categories (named "topics" in the search) considered in the mapping of the scientific articles, using the Web of Science database. These categories have been combined using the "AND" and "OR" operators (see Table 5.2)

Acronym	Category	Definition
LaU	Land use	TS=(land use OR land use change* OR land-use OR land-use change*)
LaC	Land cover	TS=(land cover OR land cover change* OR land-cover OR land-cover change*)
FoC	Forest cover	TS=(forest* OR forest cover OR forest cover change* OR forest-cover OR forest-cover change*)
BpE	Biophysical effects	TS=(biophysical effect* OR biophysical impact* OR biophysical feedback*)
ClV	Climate variables	TS=(temperature OR precipitation)
ObD	Observations	TS=(observation* OR observed OR current OR recent OR historical OR past)
MoD	Models	TS=(model*)
FuC	Future climate	TS=(climate change* OR climatic change* OR global warming)
EuR	Europe	TS=(Europe*)
NoP	No paleo studies	NOT=(paleo OR glacial OR quaternary OR Pleistocene OR Holocene OR Devon*)

The number of articles is further reduced when the climate variables are specified as temperature or precipitation and when the data used in the respective study (observations or models) are included. For these "… AND BpE AND ClV AND (ObD OR MoD)" categories, several hundred scientific articles have been identified, ranging between 155 for the land cover and 297 for the land use and 372 when all three states of the land are combined. In addition to the scientific articles, review papers have been identified in these categories. The respective numbers vary between 8 (land cover) and 9 (land use and forest cover) and 16 for the combination of the three land states. The lists of the 372 scientific articles and of the 16 review papers, including the abstracts for each category of publications, for the combination of the three land states can be found as Electronic supplements (E1, E2). Figure 5.1 shows the number of scientific articles in the aforementioned categories for individual years between 2000 and 2018. Note that for 2018 only the first 8 months of the year have been considered. The distribution indicates three different stages of evolution of the field with few articles in the first five years (2000-2004), about twice as many in the next six years (2005-2010) and an increasing number of articles after 2010. According to a corresponding search for the longer period 1900-2018, the first relevant article had been published in 1991 and there were only 23 articles during the 1990s. (see Electronic supplement E3 for the list of papers and the abstracts). Distinguishing between observations and models as the basis of the articles shows that, independent of the state of the land, more (one third for "LaU OR LaC OR FoC…") studies are based on models than on observations (see Table 5.2). Furthermore, a large fraction (two thirds for "LaU OR LaC OR FoC…") of the articles based on models deal with future climate. Only very few (6-8%) of the relevant studies have a focus on Europe.

Table 5.2: Number of scientific articles in specific categories (see Table 5.1 for details) in the period 2000-2018 according to the Web of Science database. In parentheses, the number of review papers for the "… AND BpE AND ClV AND (ObD OR MoD)" categories are given. For land use and land cover, the mapping was done on August 29, 2018, and for the forest cover on August 30, 2018

	LaU	**LaC**	**LaU OR LaC**	**FoC**	**LaU OR LaC OR FoC**
	116,129	43,829	172,798	245,918	380,039
AND BpE	1,312	590	1,366	1,132	1,955
AND BpE AND ClV	297	182	321	258	441
AND BpE AND ClV AND (ObD OR MoD)	253 (9)	155 (8)	274 (11)	218 (9)	372 (16)
AND BpE AND ClV AND (ObD OR MoD) AND EuR	18	12	21	13	24
AND BpE AND ClV AND ObD	168	109	183	134	234
AND BpE AND ClV AND MoD	215	129	230	178	309
AND BpE AND ClV AND MoD AND FuC	157	96	166	123	207
AND BpE AND ClV AND MoD AND FuC AND EuR	11	8	13	9	14

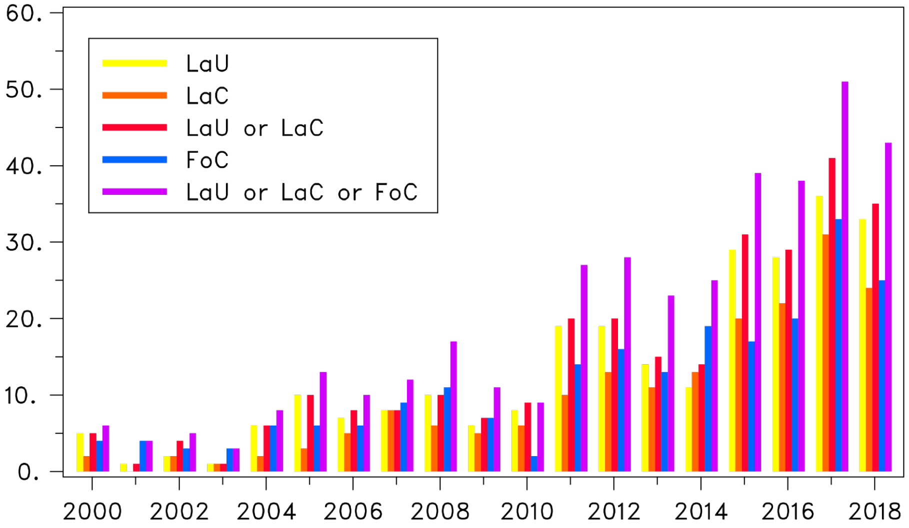


Fig. 5.1: Number of scientific articles per year for the specific categories "… AND BpE AND ClV AND (ObD OR MoD)" (see Tables 5.1 and 5.2 for details) according to the Web of Science database. Note that for 2018 only the first 8 months of the year are considered

The search in the GS database applying "… AND ("biophysical effect" OR "biophysical impact") AND ("temperature" OR "precipitation") -paleo -glacial -quaternary -Devon -Holocene -Pleistocene" for the three different states of the land gave a similar numbers of items, on the order of several hundred (see Table 5.3). The numbers vary between 172 for land cover to 393 for land use and reach 496 for the combination of the three land states. This means that the variation between the different states of the land is consistent for the two databases. The GS database, however, is much less restrictive than the WoS database. While the WoS database only includes scientific articles (which, in addition, have to be published in a volume of a specific scientific journal), the GS database also includes conference abstracts, book chapters, etc. Therefore, we went through the original list of 496 publications for the combination of the three states and subjectively omitted those publications that were not scientific articles published in a scientific journal. In the end, only 149 scientific articles (the list can be found as Electronic supplement E4) were left. This is considerably less than the 372 articles that were identified in the WoS database in a similar search. This might be due to the fact that the "topics" in the WoS database is less restrictive than the search for "words" in the GS database. Moreover, there is little overlap between the results obtained from the two databases. Only 16 scientific articles have been identified in both databases.

Table 5.3: Number of publications (excluding patents and citations) in specific categories in the period 2000-2018 according to Google Scholar. In parentheses, the number of scientific articles for the "("land use" OR "land cover" OR "forest") AND…" category (omitting abstracts, book chapters, etc.) is given. The mapping was done on September 3, 2018

	"land use"	**"land cover"**	**"land use" OR "land cover"**	**"forest"**	**"land use", "land cover" OR "forest"**
AND ("biophysical effect" OR "biophysical impact") AND ("temperature" OR "precipitation") -paleo -glacial -quaternary -Devon -Holocene -Pleistocene	393	172	406	390	496 (149)

The little correspondence between the search results from the two databases was unexpected. Apparently, the results from the mapping of the scientific literature strongly depend on the content of the database, the search options available and the details of the search protocol. On the other hand, the little correspondence emphasizes the importance of combining search results from several databases, as we have done here. Also compared to the scientific articles identified in the review paper by Perugini et al. (2017; see Chapter 4.1), we find only little correspondence between the selected scientific articles. Out of the 28 articles that fulfilled the eligibility criteria set in the review, only five have been identified in the WoS database and three in the GS database, but the three latter articles appear in both databases. In the light of these limitations, we will primarily use the results from the mapping of the scientific literature as background information and as hints on scientific articles from research fields with which we are not familiar. Instead, we have drawn on our rich experience on the subject of the synthesis to recognize the most relevant scientific journals and relevant scientific articles and followed up on the references in the papers we have looked at in the beginning, following a snowball sampling approach. In addition, we have utilized the information presented in several review papers related to the subject of the synthesis, i.e. Anderson et al. (2011), Pielke et al. (2011), Mahmood et al. (2014) and Perugini et al. (2017).

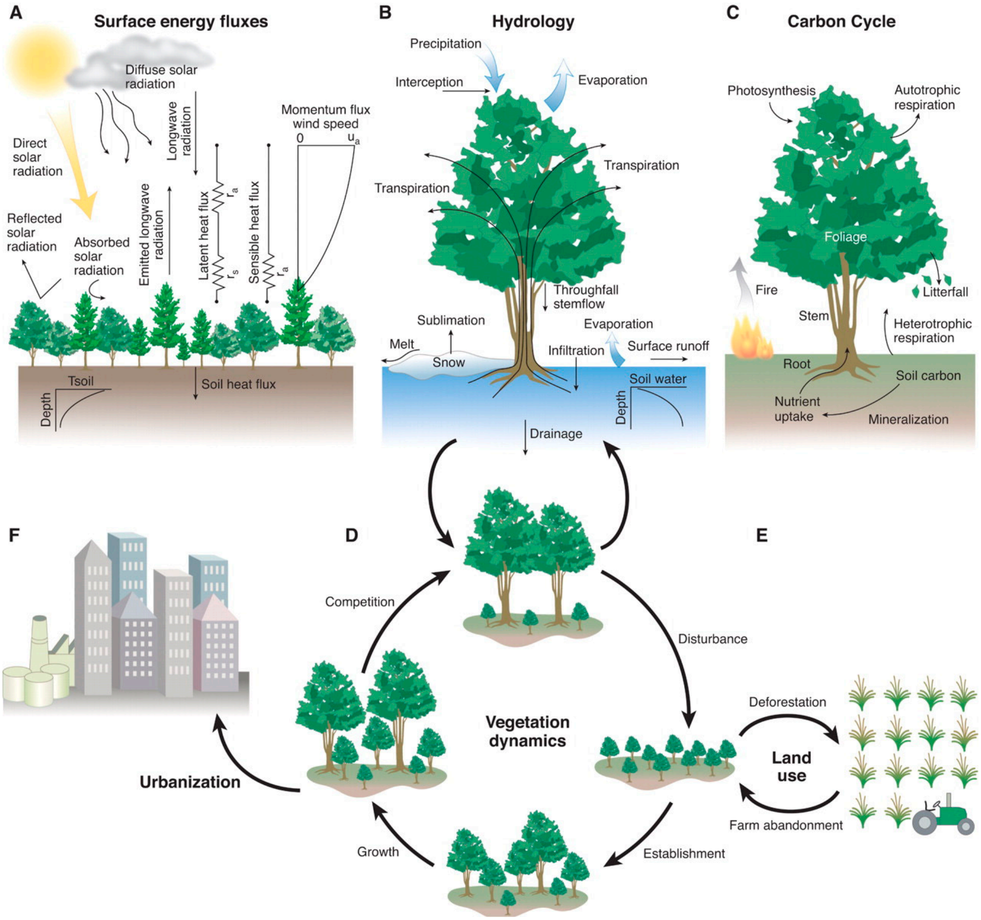


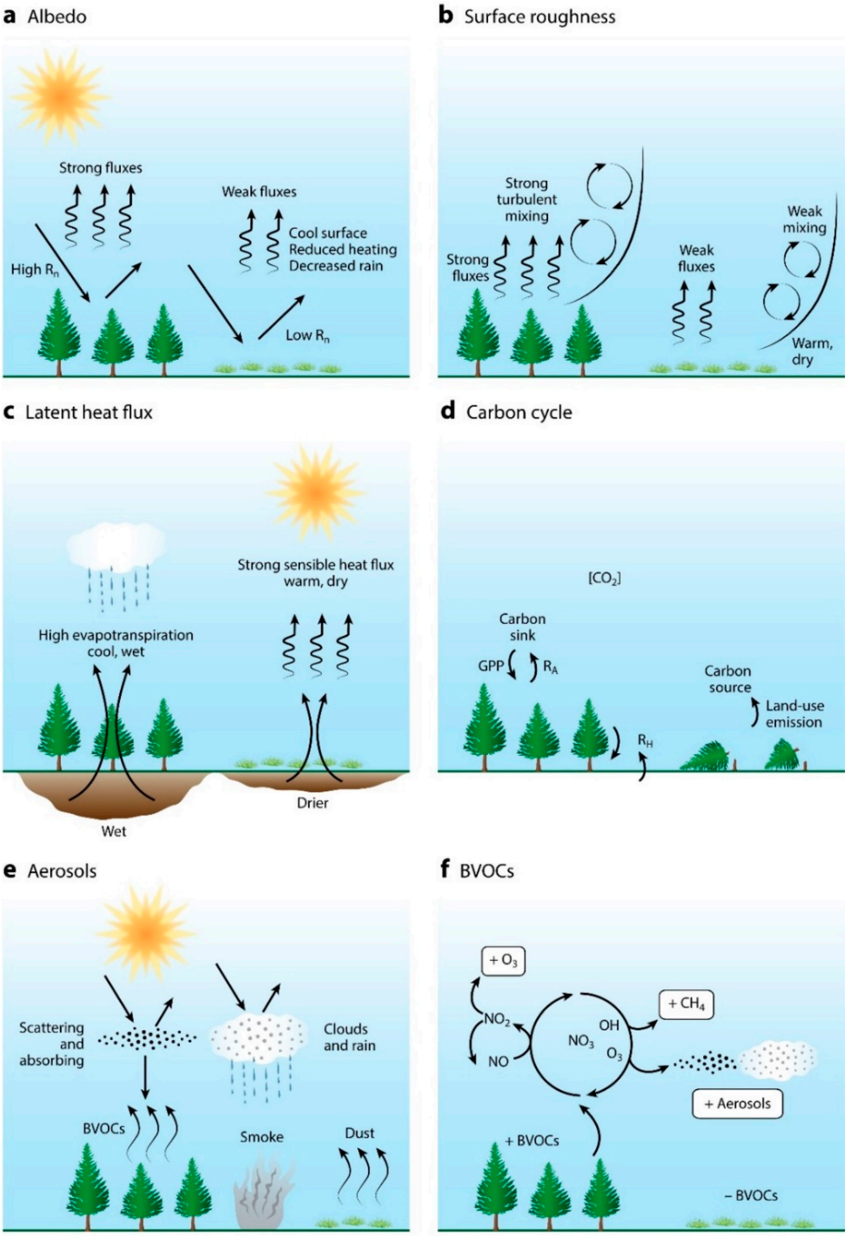
Fig. 5.2: Representation of biosphere and atmosphere as a coupled system in climate models. Land surface parameterizations represent the biophysics, biogeochemistry and biogeography of terrestrial ecosystems. Surface energy fluxes (A) and hydrology (B) are the core biophysical processes, the carbon cycle (C) the core biogeochemical process. Vegetation dynamics (D) incorporate the response of plant ecosystems to climate change, land use (E) and urbanization (F) represent human alteration of the biosphere. From Bonan (2008)

5.2 The land-atmosphere system

Land and the atmosphere interact with each other through the exchanges of momentum and energy, the exchange of water and the exchange of GHGs and other gases, aerosols and BVOC at the land surface. Furthermore, vegetation responds to the climate conditions. Figure 5.2 illustrates the land-atmosphere system with its extensive network of couplings and feedbacks exemplified by forests, in the way it is typically represented in climate models, incorporating surface energy fluxes, the hydrological and the carbon cycle. The surface energy fluxes and the hydrological cycle represent important biophysical interactions and feedbacks, and the carbon cycle is an important biogeochemical interaction. The biogeography of terrestrial ecosystems is changed, as vegetation responds to climate and as the consequence of human activities, i.e. LULCC and land management as well as urbanization.

5.3 Biophysical effects

Biophysical interactions govern the exchanges of momentum, heat and water between land and atmosphere. These affect the dynamics of the ABL, i.e. the wind speed, temperature, humidity and precipitation, and the atmospheric radiative balance (see Figs. 5.2A, B). One of the primary influences of forests is through the surface albedo, i.e. the reflectivity of shortwave radiation at the land surface (Fig 5.3a). Forests have a lower surface albedo than pastures and cropland, in particular if the ground is covered with snow. The albedo of coniferous forest (0.05-0.15) is somewhat lower than for deciduous forest (0.15-0.20), while grassland and cropland have an albedo in the range of 0.16-0.26 and of 0.18-0.25, respectively (Bonan 2015). In comparison, fresh snow has an albedo in the range 0.80-0.95 and old snow in the range 0.45-0.70. Thus, deforestation increases the albedo, while re- and afforestation have the opposite effect. An increase in surface albedo associated with deforestation decreases the absorption of solar radiation at the surface and, thus, reduces the net radiation reaching the land surface, leads to weak turbulent fluxes and cools the surface. The surface heating of the ABL decreases and possibly precipitation is reduced. In contrast to this, a decrease in surface albedo resulting from re- or afforestation increases the absorption of solar radiation at the surface and, thus, increases the net radiation and leads to strong turbulent fluxes and a warming of the ABL. In boreal regions, re- or afforestation leads to an even stronger warming of the ABL in winter. This is because the canopy of forests, in particular coniferous forests, masks snow, leading to an even greater decrease in the surface albedo compared to grassland. This, in turn, leads to stronger net radiation at the land surface and, thus, to stronger sensible heat fluxes and a warming over the forested area (Anderson et al. 2011).



Bonan GB. 2016.
Annu. Rev. Ecol. Evol. Syst. 47:97–121

Fig. 5.3: Selected forest-climate influences: (a) surface albedo and net radiation (Rn), (b) surface roughness and turbulent mixing, (c) evapotranspiration, precipitation and surface heating, (d) cycling of carbon through gross primary production (GPP), autotrophic respiration (RA), heterotrophic respiration (RH) and land use, (e) aerosols, radiation and clouds, (f) biogenic volatile organic compounds (BVOCs), atmospheric chemistry and secondary organic aerosols. From Bonan (2016)

Trees are taller than grasses and crops and are aerodynamically rougher (Fig. 5.3b). This means that the roughness length (i.e. the height above the surface where the mean winds vanish) increases. Above this level, the mean winds normally follow a logarithmic profile through the ABL. Tall grass and crops have a roughness length of up to 10 cm and up to 20 cm, respectively, while trees have a much larger roughness length of up to 6 m (Bonan 2015). Rough land surfaces create more turbulence and have stronger fluxes of sensible and latent heat than smoother land surfaces, all other factors being equal. A decrease in the surface roughness in association with deforestation results in weak turbulent fluxes and weak turbulent mixing and, thus, can lead to particularly warm and dry conditions in the ABL. An increase in the surface roughness, on the other hand, leads to strong turbulent fluxes and strong turbulent mixing.

As trees have a larger leaf area and deeper roots than grass and crops, they are able to transpire more water. Furthermore, trees can often hold more water in the canopy after rainfall events because of their larger leaf area. Therefore, forests can have high evapotranspiration rates (latent heat fluxes) compared to grasslands (Fig. 5.3c). The high latent heat flux cools the surface and moistens the ABL and, possibly, initiates clouds and precipitation. A decrease in the latent heat fluxes associated with deforestation warms the surface and leads to stronger fluxes of sensible heat and, thus, a warming of the ABL. The ABL is also dryer, which may reduce precipitation.

In the boreal regions, afforestation with mainly coniferous trees has opposite biophysical effects on the temperatures in the ABL in different seasons. In late winter and early spring, the forests have a warming effect because of the decreased surface albedo associated with the masking of snow by the canopy. In late spring, on the other hand, the forests induce a cooling effect because of the increased evapotranspiration linked to more vegetation (Alkama and Cescatti 2016). These two biophysical effects are also relevant for the boreal regions under future climate conditions. In response to the projected future warming, the treeline is expected to migrate northward and upward, and the productivity of vegetation will increase due to an extension of the growing season and the fertilizing effect of CO_2 (e.g. Wramneby et al. 2010, Garnaud and Sushama 2015). Similar to afforestation in the boreal regions, these changes in the terrestrial ecosystems have an overall warming effect due to the biophysical effects (see below).

Effects on mean temperatures

Perugini et al. (2017) assessed the biophysical effects of anthropogenic LCC on temperature and precipitation on the basis of selected scientific publications (see Chapter 4.1). Out of the 28 included studies, three were based on observations and 25 on model simulations. These simulations were designed to estimate the biophysical effects of complete deforestation or afforestation, either regionally (i.e. for climate zones) or globally, giving them an idealized character. In some of the model simulations forest was replaced by grassland, in others by bare soil. Figure 5.4 and 5.5 (see below) summarize the biophysical effects of complete regional or global deforestation on annual mean temperatures and precipitation (see Chapter 5.3), distinguishing between different climate zones, based on the 28 studies.

As a response to regional deforestation, the majority of the model simulations (marked by the black symbols) are characterized by a cooling effect in the boreal regions, a slight cooling in the temperate zone and a warming in the tropics (Fig. 5.4a). Observations (indicated by the red symbols) confirm the simulated cooling effect in the boreal regions and the warming in the tropics, but show a slight warming in the temperate zone. Regional afforestation shows the opposite, with warming effects in the boreal regions and the temperate zone and a cooling in the tropics in the model simulations (Fig. 5.4b). Again, observations give the opposite effect, i.e. a cooling effect, compared to the simulations in the temperate zone. The discrepancies between observations and the simulations can to some extent be explained by alterations of the large-scale atmospheric circulation that redistribute the anomalous energy fluxes due to the changes in forest cover (e.g. Swann et al. 2012).

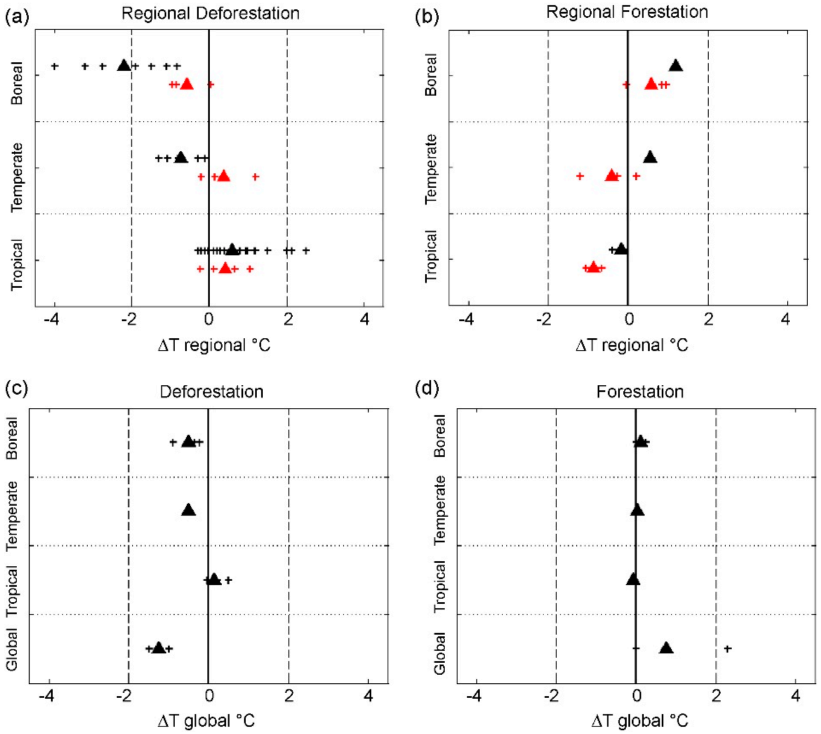


Fig. 5.4: Biophysical effects of complete regional deforestation and forestation on regional and global annual mean surface air temperatures (°C). Red crosses represent observational results, whereas black crosses represent results from model simulations. The filled triangles are the mean of each cluster. (a) and (b) show the regional temperature change associated with regional deforestation and forestation, (c) and (d) show the global temperature change associated with regional and global deforestation and forestation. From Perugini et al (2017)

Table 5.4 gives the values of the biophysical effects of LCC on annual mean temperatures and precipitation averaged over the available studies (marked as black or red filled triangles in Fig. 5.4) in the boreal regions relevant to this synthesis. The simulated warming effect of the transition from grassland to forest was estimated at 1.20 °C and the cooling effects of conversions from forest to grassland or bare land are assessed as 1.96 and 2.41 °C, respectively. Observations give a much weaker effect, i.e. a warming effect of about 0.60 °C for afforestation and a cooling effect of the same magnitude for deforestation. The cooling effect of deforestation in boreal regions simulated by the models and partly confirmed by observations, indicates the dominating effect of the surface albedo, as it is the only kind of biophysical interaction leading to a decrease in near-surface temperatures associated with deforestation. In particular, removing the snow masking effect of coniferous trees increases the surface albedo in winter and early spring in boreal regions.

Table 5.4: Changes in annual mean temperature and precipitation in the boreal regions in response to regional and global land cover changes (i.e. complete deforestation or forestation), either based on model simulations ("Mod") or observations ("Obs"). The range of different model results and different observational data sets are added to the mean differences (lower part of the respective cell) where available. Adapted from Perugini et al. (2017), where also details on the included studies are given

	Temperature		**Precipitation**	
Data base / Land-cover change	**Difference / Range [°C]**	**Number of studies**	**Difference / Range [mm/year]**	**Number of studies**
Mod / Grassland –> forest	1.20	1		
Mod / Forest –> grassland	-1.96 -4.00 – -0.82	4	-58	1
Mod / Forest –> bare land	-2.41 -3.20 – -1.50	4	-88 -110 – 18	6
Mod / Shrub land –> bare land			-77 -110 – 0	6
Obs / Forestation	0.59 -0.04 – 0.95	3		
Obs / Deforestation	-0.59 -0.95 – 0.04	3		

Two kinds of observational data are used for assessing the biophysical effects of land-cover changes, i.e. in situ-based (e.g. Lee et al. (2011), Zhang et al. (2014a)) and satellite-based data sets (e.g. Alkama and Cescatti (2016), Ma et al. (2017)). The studies based on in-situ data utilize observations from pairs of locations, a forested and a non-forested location with similar climate conditions, and analyse the differences between these pairs to assess the biophysical effects of LCC on climate at a local scale (e.g. Lee et al 2012). The studies based on satellite data, on the other hand, relate the temporal change in land cover to the local changes in climate over a specific time period to assess the biophysical effects of LCC on climate at the location of the land-cover changes (e.g. Alkama and Cescatti 2016).

Observations indicate that the biophysical effects of changes in the forest cover on near-surface temperatures depend on the geographical latitude, roughly separating the boreal regions and the temperate zone of the Northern Hemisphere. When investigating the effects of small-scale clearings at sites in the Americas and Asia, Zhang et al. (2014a) found a cooling of the annual mean temperatures over open land north of about 35 °N and a warming south of this latitude on both continents. When studying the biophysical effects of potential forest conversions in China, Ma et al. (2017) identified different behaviour south of 40 °N and north of 48 °N, with a transition zone in between. Compared to cropland, the temperate forest showed a cooling effect of 0.61±0.02 °C (annual mean values) in the southern part of the country and a warming effect of 0.48±0.06 °C in the northern part of the country. Changes in forest cover have, however, different effects on daily minimum and daily maximum temperatures. Zhang et al. (2014a) found that the warming effect over open land south of 35 °N was related to an increase in daily maximum temperatures with little change in daily minimum temperatures, while the cooling effect to the north was due to a decrease in daily minimum temperatures. Lee at al. (2011) showed consistent results for North America, where the cooling effect of 0.85±0.44 °C over non-forested areas north of 45 °N was due to a decrease in daily minimum temperatures, associated with the reduced roughness length. Even though the lower roughness contributes to a warming of the daily mean temperature, at night open land cools more than forests in both the northern and the southern latitudes. This is confirmed by Alkama and Cescatti (2016), who analysed the impacts of recent losses in forest cover on near-surface and land-surface temperatures over the boreal zone. For both the near-surface and the land-surface temperatures the authors found cooling trends in daily minimum and warming trends in daily maximum temperatures in response to deforestation and the opposite tendencies associated with afforestation. These effects were somewhat stronger for land-surface temperatures than air temperatures.

These biophysical effects of land-cover changes on near-surface temperatures result from a balance of opposing effects on the surface energy balance (see above). Forzieri et al. (2017), for instance, related a warming trend in the boreal regions in response to a widespread greening of the Earth in recent decades, as documented by Zhu et al. (2016), primarily to a reduction of the surface albedo. The authors estimated that the changes in land cover (described via the LAI) amplified the ongoing warming trend in the boreal regions over the last 30 years by about 10% through biophysical interactions. According to Ma et al. (2017), the different biophysical effects of potential forest conversions in China south of 40 °N and north of 48 °N were primarily due to the net impact of the changes in latent heat fluxes (due to changes in evapotranspiration) and of the changes in the absorption of shortwave radiation (associated with changes in surface albedo). The cooling effect of afforestation in the southern part of the country was due to a strong increase in latent heat fluxes, only slightly offset by a weak increase in absorbed shortwave radiation. The warming effect in the northern part, on the other hand, was associated with an increase in the absorbed shortwave radiation, in particular in late winter and early spring, only partly offset by increases in latent heat fluxes during early summer.

Combining satellite data and other global observations with predictions from an empirical model, Bright et al. (2017) analysed the local temperature responses to a number of changes in land cover and land management, including transitions from grassland to deciduous and evergreen needleleaf trees, respectively, and from deciduous to needleleaf trees. For all three transitions, biophysical interactions resulted in a warming effect in the boreal regions, particularly during winter. The authors defined an index to measure the relative contributions of different biophysical processes to the local temperature changes associated with these conversions, i.e. the redistribution factor of energy (determined by the partitioning of sensible and latent heat fluxes and surface roughness and the exchange of heat at the surface) vs. the net radiation at the surface (determined by the surface albedo). They found that for conversions from grassland to forests the effects in the boreal regions were mainly related to the redistribution of energy, while for the transition from deciduous to evergreen needleleaf forest the net radiation was the dominating factor.

The Land-Use and Climate, Identification and Robust Identification (LUCID) project was designed to assess the robustness of the biophysical impacts of historical LULCC (e.g. De Noblet-Ducoudré et al. 2012). The experimental setup of this project consists of four simulations with several participating atmospheric general circulation models (GCMs) interactively coupled to a land surface model, with sea surface temperatures (SSTs) and sea-ice extent prescribed from coupled atmosphere-ocean simulations of the respective climate model. Two simulations for pre-industrial (1870-1900) and two simulations for present-day conditions (1972-2002) were performed. For both the pre-industrial and the present-day period, in one simulation the vegetation map from 1870 was prescribed and in the other the vegetation map from 1992. The results from seven participating models were analysed for North America and Eurasia, covering mainly the temperate climate zone (about 40-60 °N in Eurasia). In these regions, large fractions of the forests had been replaced by crops and pasture between 1870 and 1992.

In Eurasia as well as in North America, the simulations gave an overall cooling of the near-surface temperatures in all seasons associated with the aforementioned land cover changes (De Noblet-Ducoudré et al. 2012). The cooling effect was relatively strong in spring and summer and somewhat weaker in autumn and winter. Thus, the biophysical effects of anthropogenic LCC counteracted the overall warming trend due to increased anthropogenic climate forcing. The cooling effect was related to a consistent increase of the surface albedo in all models. During summer, the magnitude of this increase corresponded very well to the extent of the deforested area in the majority of the models. The higher surface albedo caused a decrease in the available energy (the sum of the absorbed shortwave radiation and atmospheric longwave radiation). Consistent with the albedo, the magnitude of the change in the available energy corresponded to the extent of the deforested area. The reduced available energy is accompanied by a decrease in the turbulent energy fluxes (the sum of latent and sensible heat fluxes). In addition, the fraction of the available energy used for turbulent energy fluxes is reduced in response to LCC. Crops and grasslands are typically less efficient than trees in transferring energy to the atmosphere through turbulent fluxes because of the reduced surface roughness.

Lejeune et al. (2018) followed up on the LUCID project, combining the simulations from LUCID with simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al. 2012) multi-model experiment, including simulations from 11 different ESMs. As the simulations from CMIP5 did not comply with the experimental design from LUCID, the authors had to apply a specific method, which allows for separating the biophysical effects of anthropogenic LCC from other forcing factors (Kumar et al. 2013). Both sets of experiments showed a reduction of the mean winter temperatures in the Northern Hemisphere mid-latitudes in response to historical LCC, caused by increases in the surface albedo. In Eurasia, the LUCID experiment gave an average cooling of 0.2 °C and the CMIP5 simulations a slightly stronger cooling of 0.3 °C. Also the mean spring temperatures were reduced to some extent in both sets of experiments, while the temperatures during summer and autumn were increased in the majority of the participating models. Lejeune et al. (2018) also studied the biophysical effects of LCC on daily minimum and maximum temperatures and on the daily temperature range as simulated by the models. They found that none of the models was able to capture well the observed increase of the daily temperature range in response to deforestation (Lee et al. 2011). Overall, however, the CMIP5 models were better at simulating both the observed cooling of daily maximum temperatures in summer and the observed warming the daily minimum temperatures in winter than the models from LUCID.

As mentioned above, studies on the biophysical effects of land-cover changes on climate based on observations only represent the local effects and neglect non-local effects that influence climate in remote regions due to changes in the global atmospheric circulation. In most studies employing climate models, on the other hand, the local biophysical effects of LCC on climate are mingled with the non-local effects, as changes in the large-scale circulation are incorporated. In some cases, the inclusion of non-local biophysical effects on climate can explain discrepancies between the results based on observations and the results based on simulations (e.g. Perugini et al. 2017). Winckler et al. (2017) developed a specific approach, which allows to distinguish between the local and the non-local biophysical effects of LCC and in a climate model and, thus, to identify robust local effects that can be consistently compared to results based on observations. In this approach, land-cover is changed in some grid cells of the model while it remains unchanged in others. It is assumed that the simulated total biophysical effects of the LCC at grid cells with LCC consists of the sum of the local and non-local effects, while the simulated effects at grid cells without LCC consists of only the non-local effects. These non-local effects are spatially interpolated to the grid cells with LCC, and the difference between the simulated total effects at grid cells with LCC and the interpolated estimates of the non-local effects then yield the local biophysical effects of LCC at these grid cells.

Winckler et al. (2019a) used this approach to investigate whether the non-local biophysical effects can explain the discrepancies between observed and simulated effects of deforestation on near-surface temperatures. Observation-based data sets largely agree on a warming in most regions due to the local effects of deforestation, especially at low and mid-latitudes, while there is less agreement about a slight cooling from the local effects of deforestation at high latitudes (Winckler et al. 2019a). Thus, observations indicate a global-scale warming induced by deforestation. Simulations of the effects of global deforestation, however, are generally characterized by a cooling of the global mean temperatures due to substantial cooling in the temperate and boreal zones (e.g. Devaraju et al. 2015). The results from Winckler et al (2019a) indicated that the non-local biophysical effects of deforestation lead to a cooling of the global mean temperature, regardless whether deforestation was implemented at low, intermediate or high latitudes. In the cases of deforestation at low and mid-latitudes, this cooling exceeded the warming due to the local biophysical effects of deforestation resulting in a cooling as the total biophysical effects. At high latitudes, on the other hand, the local biophysical effects of deforestation were found to be negligible, so that the non-local effects dominate the combined effects. In conclusion, the simulated local biophysical effects of deforestation were found to be compatible with observations, while the simulated non-local effects, typically governing the combined effects, were reversed.

Winckler et al. (2019b) also applied this method to study the importance of the local biophysical effects of changes in the surface roughness of deforestation as compared to the local effects of the changes in surface albedo. This was done on the basis of four specific climate simulations, one with forests prescribed at all grid cells where forests would be able to grow and three where these grid cells are deforested following the approach mentioned above. In one of these simulations all of the surface properties were switched from forest to grassland, in the two other simulations only surface roughness or surface albedo were switched from forest to grassland. The authors found that the local biophysical effects of the reduced surface roughness from deforestation dominated the effects on several aspects of near-surface temperatures, i.e. the annual and seasonal mean temperatures as well as the diurnal temperature range. In the boreal regions the reduced surface roughness was found to substantially contribute to an overall winter cooling in response to deforestation.

When Wramneby et al. (2010) and Zhang et al. (2013, 2014b) used RCA-GUESS to investigate the biophysical effects of future changes in natural vegetation on climate in

Europe and the boreal zone, respectively, they did not consider any anthropogenic land-cover changes. In contrast, Gao et al. (2014) applied the REMO RCM to investigate the biophysical effects of peatland forestation in Finland before the drainage (1920) and after the drainage (2000s). The authors found that the peatland forestation induced a warming in spring, i.e. the snow-melting season, and a slight cooling in the growing season (May through October) in the affected regions. The warming in spring was mainly caused by decreased surface albedo and the cooling in the growing season by increased evapotranspiration. Strandberg and Kjellström (2019) used simulations with the RCA RCM to investigate the climate impacts of maximum afforestation or deforestation in Europe, focussing on the effects on seasonal mean temperatures and precipitation as well as daily temperature extremes. The simulations indicated that afforestation in Europe generally resulted in increased evapotranspiration which, in turn, lead to colder near-surface temperatures. Deforestation gave the opposite effects, with warmer near-surface temperatures due to decreased evapotranspiration. In regions with limited evapotranspiration, however, changes in the surface albedo were relatively more important for temperatures. The study also showed that the climatic effects of afforestation or deforestation in Europe were mainly local.

Effects on temperature extremes

The particularly strong effects of LULCC on daily maximum temperatures in the Northern Hemisphere mid-latitudes (e.g. Alkama and Cescatti 2016) suggest that anthropogenic land-cover changes affect temperature-related extremes. Understanding these effects is important if changes in land use or land cover are promoted to mitigate the impacts of the projected future increases in the intensity of climate extremes.

Teuling et al. (2010) investigated the responses of the energy exchanges over forests and grassland during European heatwaves (i.e. in 2003 and 2006), using observations from an extensive network of flux towers in Europe located in forested areas and grasslands, respectively. The authors identified differences in the temporal responses of forest and grassland ecosystems during these heatwaves. Initially, the surface heating was twice as high over forests than over grassland in association with intensified sensible heat fluxes over the forests. Over grass, the heating was suppressed by increased evaporation in response to increased solar radiation and temperature, as a relatively large fraction of the additional energy is used for evaporation of water rather than increasing the sensible heat. This process, however, accelerated the depletion of soil moisture and induced a shift in the regional climate system that led to increased heating. This means that the conservative use of water in particular forest ecosystems contributes to increased temperatures in the short term but can mitigate the impacts of the most intense heatwaves or long-lasting events on longer timescales.

Pitman et al. (2012) extended the study by De Noblet-Ducoudré et al. (2012) and used a sub-set of the simulations from the LUCID project to analyse the effects of historical land-cover changes on extremes related to daily temperature in boreal spring and summer. According to this study, the historical transitions from natural vegetation to cropland or pasture in large parts of North America and Eurasia (mainly in the temperate climate zone) resulted in a cooling of the daily mean temperatures in both seasons according to three out of the four climate models considered in the study, while one model simulate a warming in summer and a cooling in spring. As for the seven cases (i.e. seasons and models) with decreased mean temperatures, the cooling goes along with an overall weakening of extreme values derived from daily maximum temperatures (number of warm days or nights, warmest seasonal daily maximum temperatures, warm spell duration) and a strengthening of the extreme values derived from daily minimum temperatures (number of cold days or nights, coldest seasonal daily minimum temperatures, cold spell duration) over North America and Europe. In the remaining case with increased mean temperatures, on the other hand, the warming goes along with a strengthening of the extreme values derived from daily maximum temperatures, particularly in Eurasia.

Lejeune et al. (2018) obtained contrasting results on the effects of historical deforestation in their study, where they not only used more advanced ESMs but also constrained their analysis by only using those models (five out of 11) that gave results for the changes in daily maximum temperatures consistent with observations (e.g. an observed increase of the mean daily maximum temperatures by 1.16 °C during boreal summer over North America [Lee et al. 2012]). The five selected models simulated a corresponding warming effect between 0.12 and 0.77 °C, while the six other models gave a cooling effect between 0.00 and 0.44 °C. Over North America, all five models not only simulated increases in mean daily maximum temperatures in summer but also in the annual maximum daily maximum temperature (the hottest day of the year). Over Eurasia, on the other hand, only three out of the five selected models simulated increases in both the mean daily maximum temperatures in summer and in the hottest day of the year.

Strandberg and Kjellström (2019) also found relatively strong biophysical effects of afforestation or deforestation in Europe on daily minimum and maximum temperatures compared to the impacts on mean near-surface temperatures. In the case of afforestation, the reduced winter mean temperatures in most of Europe were contrasted by a marked warming of daily minimum temperatures. During summer, on the other hand, the marked changes in mean temperatures were mainly caused by respective changes in daily maximum temperatures, i.e. decreases in the case of afforestation and increases for deforestation.

Both the discrepancies with observation and the contrasting results on the biophysical effects of historical LULCC on mean temperatures as well as on daily minimum and maximum temperatures simulated by different climate models illustrate a high degree of uncertainty in the simulation of the biophysical interactions by the models. Although this can be partly explained by the non-local effects of LULCC (Winckler et al. 2019a), which do not impact observations, an important source of uncertainty are the representations of the relevant physical processes in the climate models themselves.

Effects on precipitation and the hydrological cycle

In addition to the terrestrial carbon cycle, trees and forests regulate the energy and the water cycles and, hence, are essential for the hydrological cycle, ranging from local over regional to global scales (Ellison et al. 2017). Forests play, for instance, an important role in regulating the fluxes of atmospheric moisture and rainfall patterns over land. At the land surface, forests and other vegetation facilitate the transfer of water from the soil into the atmosphere through evapotranspiration, i.e. transpiration through the vegetation canopy and evaporation from plant surfaces and soil. By this, forests can affect the transports of water over the continents and regulate water supplies. Afforestation or reforestation, for instance, normally leads to substantial reductions in local streamflow, while forest clearing results in increased streamflow (e.g. Andréssian 2004).

For annual mean precipitation, the review by Perugino et al. (2017) showed that the majority of the model simulations (no study based on observations was included) are characterized by less precipitation in response to regional deforestation in all the three climate zones. i.e. the boreal, temperate and tropical zone (Fig. 5.5). The effect is strongest in the tropics and weakest in the boreal region. In the boreal region, all the three different kinds of LCC (transforming forest into grassland or bare land and shrub land into bare land) are associated with reduced precipitation ranging from 58 mm/year for the transition from forest to grassland to 88 mm/year for the conversion from forest to bare land (see Table 5.4).

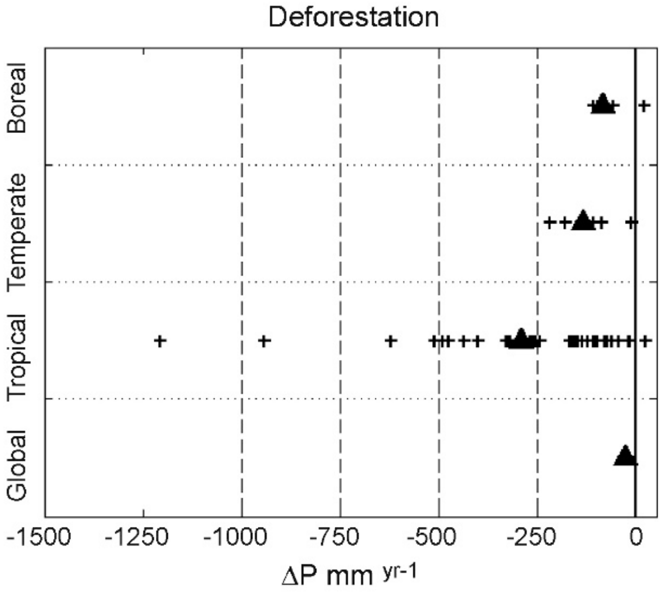


Fig. 5.5: Biophysical effects of regional or global deforestation on regional or global changes in average annual precipitation. Black crosses represent each study data point, filled triangles the average. From Perugini et al (2017)

Based on the simulations from the LUCID project, De Noblet-Ducoudré et al. (2012) also found an impact of historical LCC on the surface water balance (defined as the difference between precipitation and evapotranspiration) in Eurasia, with a slight increase in all seasons. Using observations of terrestrial evapotranspiration for discrete land-cover types, Sterling et al. (2013) investigated the impact of recent global land-cover change on the terrestrial water cycle. According to this, recent LCC has led to a reduction of the global-scale terrestrial evapotranspiration by about 5%. Applying a global land-surface model, the authors estimated that such as decrease in evapotranspiration would lead to an increase of the annual runoff by 7.6%. The impact of the land-cover changes on evapotranspiration varies regionally and is characterised by several hotspots of pronounced decreases over the western part of North America, in western and central Europe as well as in East and Southeast Asia, over western and south-eastern Africa and over the southern part of Brazil. Widespread increases in evapotranspiration were only identified in India and over some parts of Central and East Asia. Large contributions to the reduction of global terrestrial evapotranspiration were related to conversions of wetlands to non-irrigated cropland, grazing or urbanized land. Smaller contributions came from the transition from forests to non-irrigated cropland, grazing or built-up land and the conversions of grassland to non-irrigated cropland. Increases in global terrestrial evapotranspiration came mainly from transforming barren land, grassland or forest to reservoirs and to a smaller extent from transforming barren land to irrigated cropland or urbanized land. The changes in several surface variables supported the overall changes in evapotranspiration, namely changes in available water (incorporating rooting depth), changes in available energy (incorporating surface albedo) as well as changes in surface roughness and LAI.

5.4 Biogeochemical effects

Although the focus of the synthesis is on the role of biophysical interactions for regional changes in climate and ecosystems, biogeochemical interactions are at the core of current policy discussion (and existing policy instruments) with a focus on maintaining and enhancing carbon sinks to offset emissions. Biogeochemical effects have considerable impacts on climate and terrestrial ecosystems at various temporal and spatial scales. The carbon cycle is an important part of the biogeochemical interaction between land and the atmosphere (see Fig. 5.2C).

Forests, on average across the globe, absorb atmospheric CO_2 and, thus, reduce net radiation and have a cooling effect on climate (Fig. 5.3d). Some forest stands are, however, a net source for carbon, and the carbon balance (i.e. net ecosystem exchange) tends to vary from a net source to a weaker source and finally a sink in the course of forest recovery following harvest or disturbance (Hyvönen et al 2007, Williams et al. 2012). Under equilibrium, forests, like other ecosystems, are expected to be carbon neutral, with carbon loss through phenological turnover, mortality and decomposition matching plant productivity on average over large areas (e.g. Keenan and Williams 2018). The drivers and location of the current biospheric carbon sink remain a matter of scientific debate, but attribution studies based on atmospheric measurements, remote sensing and modelling tend to identify clear sinks in the tropics, low-latitude semi-arid ecosystems as well as temperate and boreal forests (Pan et al. 2011, Ahlström et al. 2015, Schimel et al. 2015). CO_2 fertilisation is considered a strong driver for the terrestrial carbon sink, but demographic recovery following past land use likely provides an equally important explanation for industrialised regions of North America, Europe and Asia (Pugh et al. 2019). Deforestation, on the other hand, can lead to a release of carbon and to an increase in net radiation and, thus, a warming effect on climate. Furthermore, carbon emissions due to anthropogenic LULCC may counteract the carbon sink of forest ecosystems. In contrast to the biophysical effects and some of the other biogeochemical interactions, the biogeochemical interaction associated with the carbon cycle has global impacts and operates at very long time scales. This is due to the long lifetime of CO_2 in the atmosphere.

The biogeochemical effect of LULCC on the carbon cycle is mainly related to differences in carbon stocks, storage capacity and residence time in various terrestrial ecosystems. The amount of carbon stored in vegetation and soils is typically larger for forests than for grassland or cropland. Dejavaru et al. (2015) presented estimates of these carbon stocks, arriving at about 410 t C per hectare (ha; 1 ha is 10,000 m^2) for boreal forests, 240 t C/ha for tropical forests as well as for grasslands and shrub lands, 150 t C/ha for temperate forests and 80 t C/ha for croplands, respectively. Using a book-keeping approach, Le Quéré et al. (2018) estimated that the conversion of forests into agricultural land during the last two and a half centuries (1750-2017) has released 235±95 Gt C, with a large fraction of 190±75 Gt C after 1870. Simulations with DGVMs, however, suggest that such estimates of the released carbon due to historical LULCC could be substantially underestimated because processes such as tree harvesting and land clearing from shifting cultivation have not been considered (Arneth et al. 2017). The associated emissions of CO_2 have led to a considerable global warming although a large fraction of the CO_2 has been removed from the atmosphere, an estimated 195±50 Gt C of this by terrestrial sinks (Le Quéré et al. 2018).

Research has strongly focussed on the carbon cycle with CO_2 as a GHG and much less on the methane and nitrogen cycles, with emissions of CH_4 and N_2O, respectively, into the atmosphere. In the Swedish context, CH_4 plays an important role in the permafrost areas in northern Sweden (e.g. O'Connor et al. 2010) and both CH_4 and N_2O in peatlands (e.g. Kasimir et al. 2015). Kasimir et al. (2015) investigated, among others, the GHG emissions associated with the rewetting of drained peatlands, assuming four different scenarios: Norway spruce with an average soil water table of -40 cm, willow with groundwater at -20 cm, reed canary grass with groundwater at -10 cm and a fully rewetted peatland. The authors found substantial differences in the CH_4 emissions from the four different ecosystems (including vegetation and soils), ranging between -0.2 Mg CO_2-eq/ha/year (1 g CH_4 has a global warming potential of 28 g CO_2) for Norway spruce over 4.6 (willow) and 6.4 (reed canary grass) to 6.9 Mg CO_2-eq/ha/year for peatland vegetation. The emissions of N_2O showed the opposite tendency with values ranging from 2.5 Mg CO_2-eq/ha/year (1 g N_2O has a global warming potential of 265 g CO_2) for Norway spruce over 1.0 (willow) and 0.2 (reed canary grass) to virtually no emissions for peatland vegetation. The nitrogen cycle is not only directly linked to emissions of N_2O (e.g. Xu-Ri et al. 2012), it also regulates the feedbacks between the carbon cycle and climate (e.g. Thornton et al. 2009). Wårlind et al. (2014), for instance, found that nitrogen feedbacks can increase the carbon uptake of terrestrial ecosystems by 17% under future climate conditions, in contrast to other studies, which have shown an 8-37% decrease in carbon uptake under future climate conditions.

Land is also the source of different kinds of primary or secondary atmospheric aerosols (Fig. 5.3e). Biomass burning, for instance, injects black carbon and other aerosols into the atmosphere. The land surface releases aerosols from mineral dust into the atmosphere. Many trees emit BVOC, mostly isoprene and monoterpene. Under present-day climate conditions, 400-600 Mt C/year are emitted as isoprene and 30-130 Mt C/year as monoterpene (Guenther et al. 2012). There is an overall tendency of the vegetation in the tropics and the temperate zones to emit isoprene, while boreal vegetation mainly emits monoterpene. BVOC emissions strongly depend on the type of ecosystems, with strong emissions from broadleaf and needleleaf forests but weak or no emissions from crops or grassland (e.g. Schurgers et al. 2009). Also, the emissions of BVOC are very sensitive to the local climate conditions, especially temperatures, solar radiation, and the atmospheric CO_2 concentration (Arneth et al. 2007). BVOC emissions produce ozone (O_3), increase the concentration of CH_4 and form aerosols (Fig 5.3f). The latter is done by transforming a certain fraction of BVOC into biogenic secondary organic aerosols (SOA; e.g. Shrivastava et al. 2017). Given the heterogeneity of landscapes and, thus, the heterogeneity of BVOC emissions the transformations to SOA take place at very small spatial scales. The effects of aerosols on climate are complex, and they can be either direct or indirect in nature. Direct effects are the scattering of solar radiation into space and the absorption of solar radiation by the aerosols, having a cooling and a warming effect on climate, respectively (Fig. 5.3e). They also affect climate indirectly by altering the formation and the characteristics of clouds, i.e. increase the brightness of clouds, and supressing rainfall.

Unger (2014) investigated how the emissions of BVOC in relation to anthropogenic LULCC between 1850 and 2000 have contributed to the climate forcing during that period. For this, the author employed a global climate model, incorporating the carbon cycle and atmospheric chemistry. According to the estimates from this study, historic LULCC (i.e. an expansion of cropland) has led to reductions in the emissions of isoprene by about 135 Mt C/year and of monoterpene by about 52 Mt C/year. When considering other volatile organic components as well, the reduction in emissions since 1850 amounted to about 35%. As a consequence, both the atmospheric concentrations of O_3 and CH_4 and the concentrations of biogenic SOA decreased. These changes resulted in a net cooling effect of about 0.11 ± 0.17 W/m^2 between 1850 and 2000. The negative climate forcing was related to O_3 (0.13 W/m^2) and CH_4 (0.06 W/m^2), while SOA resulted in a positive climate forcing of 0.09 W/m^2. The positive climate forcing by SOA exceeded the combined negative forcing by O_3 and CH_4 in several parts of the Northern Hemisphere, i.e. the transition zones between temperate and boreal zones in North America and Eurasia as well as the tropical savannah zone south of the Sahara.

Szogs et al. (2017) applied the managed-land version of LPJ-GUESS (Lindeskog et al. 2013; see Chapter 4.3) to simulate the changes in the emissions of isoprene and monoterpene during the 20th and the 21st century. For the latter period, anthropogenic LULCC were prescribed in accordance with the land-cover changes associated with the RCP2.6 scenario. This scenario is characterized by strong mitigation efforts, either via afforestation, reforestation and avoided deforestation or by means of bioenergy in combination with BECCS. The authors distinguished between two specific land-use and land-cover scenarios in accordance with these two mitigation strategies, i.e. one with focus on afforestation and one with focus on bioenergy. For the historic period (1901-2000), the results showed considerable reductions in the emissions of both isoprene and monoterpene, in particular until about 1960. After that, the emissions stabilized as the total land area under agriculture expanded only slightly. For the 21st century, on the other hand, the BVOC emissions were projected to increase under the afforestation scenario, particularly for isoprene (with increases of about 1/3 compared to present-day values in the tropics and the temperate zone of the Northern Hemisphere) and to a somewhat lesser extent for monoterpene (with increases of about 20% in the boreal zone). Under the bioenergy scenario, the BVOC emissions increased only slightly over the course of the 21st century, mainly due to LULCC in the boreal zone. In the other climate zones, the BVOC emissions were generally reduced in this scenario.

Employing the same approach, Hantson et al. (2017) estimated the contributions of different drivers on the emissions of isoprene and monoterpene during the 20th and 21st century. The authors distinguished between climatic changes, climatic changes combined with increasing atmospheric CO_2 and climatic changes combined with both increasing CO_2 and anthropogenic LULCC as drivers. For the historic period, the simulation with climatic changes only showed increases in the emissions of both isoprene and monoterpene, especially after the 1960s in association with the accelerating global warming. The simulation also including the effect of CO_2 showed that increased levels of atmospheric CO_2 counteracted the increased emissions associated with climatic change. For isoprene, the emissions stayed at about the same level during the 20th century, while for monoterpene the emissions somewhat decreased. Historical LULCC further counteracted the increases in the emissions due to climatic changes. For isoprene, the emissions decreased during the 20th century and for monoterpene, the emissions decreased over both the 20th and the 21st century.

5.5 Combined biogeochemical and biophysical effects

A large fraction of the land surface (about 80% of the ice-free land surface; Erb et al. 2017) is under some degree of human management, and the intensity of the management has strongly increased in recent decades at a global scale. About 10% of the ice-free land surface is under intense human management, half under medium and 20% under extensive management. In their review, Erb et al. (2017) put relative weights on the biogeochemical and the biophysical impacts of different forms of land management. Grazing and mowing, for instance, is associated with strong biogeochemical but small biophysical effects, while the selection of tree species has strong biophysical but small biogeochemical effects (Fig. 5.6). Forest harvest as well as crop harvest and irrigation, on the other hand, have equally important strong biogeochemical and biophysical effects. Wetland drainage has strong biogeochemical effects and some biophysical effects. Various agricultural practices, e.g. fertilization, tillage and residue management have small biophysical but important biogeochemical effects. The effects of management activities also act on a range of timescales. While alterations of the properties of the land surface impose immediate effects on the atmosphere via their impact on the surface energy balance, changes in carbon and nitrogen fluxes delay the response to the anomalous fluxes associated with land-cover changes (Ciais et al. 2013).

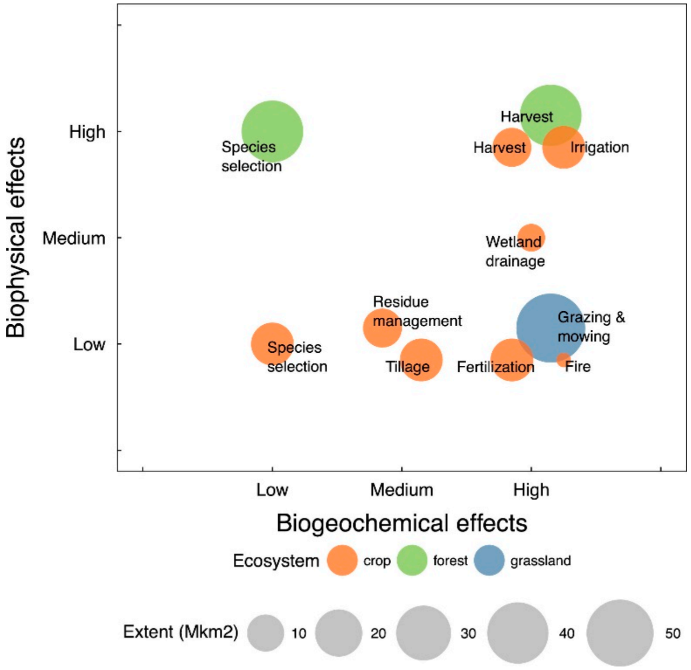


Fig. 5.6: Extent and the importance of the associated biogeochemical and biophysical effects of various land management activities. The classification is based on expert judgement. From Erb et al. (2017)

Several studies employing global climate models, including ESMs, showed marked increases in the atmospheric CO_2 concentration (biogeochemical effects) in response to (idealized) large-scale deforestation (e.g. Bala et al. 2007, Bathiany et al. 2010, Devaraju et al. 2015). Bala et al. (2007), for instance, found increases in the CO_2 concentration of 199, 110 and 5 ppm for the cases of deforestation in the tropical, temperate and boreal regions, respectively. The radiative forcing of these increases would lead to a global warming with a specific magnitude, but the biophysical effects of the large-scale deforestation influence the near-surface temperatures regionally and, hence, also the overall change in the global mean temperature. The tropical deforestation was found to cause an additional global-scale warming of 0.7 °C and the boreal deforestation a global-scale cooling of 0.8 °C through biophysical effects. The impact of the biophysical effects varies by region. In the land areas of the high northern latitudes, for instance, boreal deforestation was associated with a cooling of 3.8 °C and tropical deforestation with an additional warming of 2.1 °C. In contrast to the global mean temperature with a slight cooling of 0.04 °C, deforestation in the temperate climate zone had an additional warming effect of 0.4 °C at high northern latitudes. As a result, the biophysical effects of global deforestation result in an additional warming of 2.1 °C at high northern latitudes. The cooling effect of global-scale deforestation at these latitudes was mainly related to considerable increases in the surface albedo and partly to increases in cloudiness, both increasing the planetary albedo in these regions (Betts 2000).

Arora and Montenegro (2011) extended the strongly idealized experimental design by considering 50% of afforestation, distinguishing afforestation in the boreal, the northern temporal and the tropical latitudinal bands for the less intensive afforestation. The global afforestation (areas that either currently are cropland or currently urbanized but feasible for forest growth) led to larger carbon uptakes by the ecosystems, reducing the atmospheric CO_2 concentration by 93 ppm in the case of total afforestation and of 45 ppm for 50% of afforestation. Together with the biophysical effects, this resulted in reductions of the global mean temperatures by 0.45 °C (100% afforestation) and 0.25 °C (50% afforestation). The effects are somewhat stronger over land areas, where the mean temperatures are reduced by 0.63 °C due to 100% and 0.31 °C due to 50% global afforestation. Tropical afforestation (i.e. for 50% afforestation) alone resulted in a cooling of the land areas by 0.25 °C and afforestation in the northern temperate zone in a cooling by 0.16 °C. Afforestation in the boreal regions, on the other hand, did not have an impact on the global mean temperatures, indicating that in this case the biophysical effects offset the warming induced by the biogeochemical effects.

Instead of such an idealized experimental design, Pongratz et al. (2010) separated the strength of biogeochemical and biophysical effects on near-surface temperatures for historical anthropogenic land-cover changes. The authors found that the biophysical effects had a slight cooling effect (0.03 °C over the course of the 20th century) on the global mean temperature, while the biogeochemical effects resulted in a pronounced warming of 0.18 °C. Again, the effects were somewhat stronger for the land areas with a cooling of 0.04 °C and a warming of 0.27 °C due to the biophysical and the biogeochemical effects, respectively. This was particularly the case, when only the agricultural areas were considered, with a cooling of 0.10 °C and a warming of 0.31 °C. Although historical LCC caused a strong regional cooling through biophysical interactions during the 20th century, i.e. in North America, Europe or South Asia, the prevailing warming related to the biogeochemical effects led to an overall increase of the mean annual temperatures over most of the globe.

5.6 Overall effects of land-use and land-cover changes on climate in Sweden

Various biogeochemical and biophysical effects of re- and afforestation on near-surface temperatures in Sweden are summarized in Figure 5.7. According to this, the decrease in surface albedo (resulting in increased absorption of incoming solar radiation at the land surface) is the only effect that leads to a warming of the near-surface temperatures, while all the other effects lead to a cooling and, hence, mitigate the warming associated with climate change. As for the biogeochemical effects, these are increased carbon storage, weakening the radiative forcing, and more aerosols, which reduce the solar radiation reaching the land surface by additional scattering at the particles and more clouds. And as for the biophysical effects, these are increased roughness length, enhancing the turbulent fluxes of energy, and increased evapotranspiration in late spring and summer, which strengthens the fluxes of latent heat and weakens the fluxes of sensible heat. The magnitude of the overall cooling in Sweden associated with re- and afforestation depends on the significance of the warming effect compared to the cooling from the other biophysical and biogeochemical effects. Clear-cutting has the opposite impacts on near-surface temperatures in Sweden with all biophysical and biogeochemical effects leading to a warming except for the increased surface albedo resulting in colder temperatures.

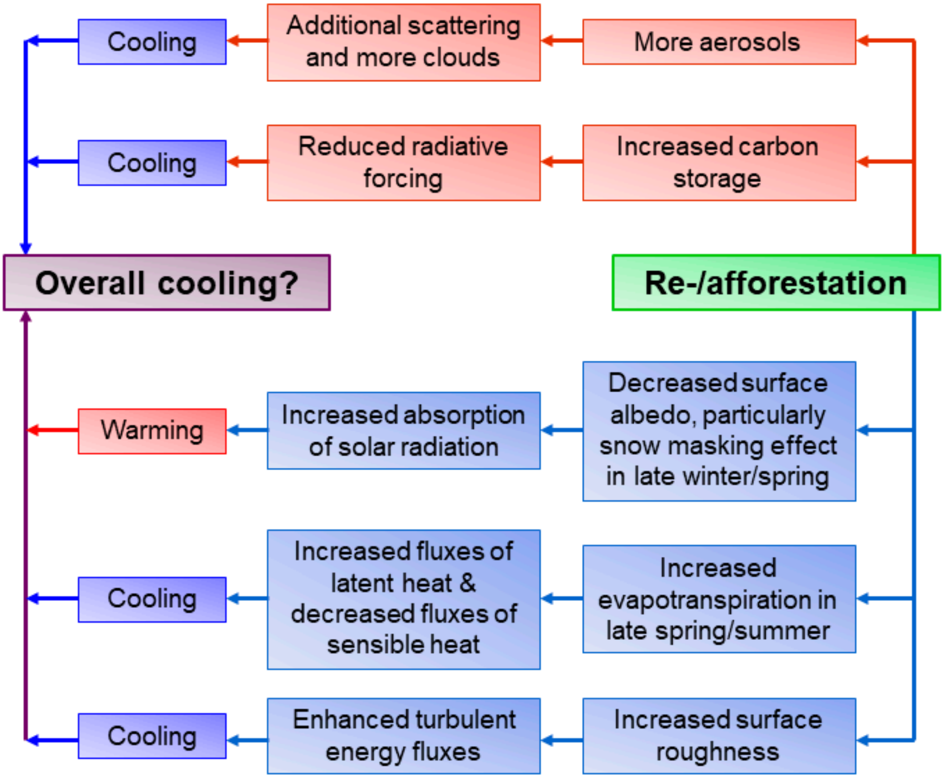


Fig. 5.7: Outline of the biogeochemical (upper part in brown) and the biophysical effects (lower part in blue) of re-/afforestation in Sweden on near-surface temperatures. Except for the effect of decreased surface albedo all effects lead to cooling and, thus, contribute to the mitigation of climate change. The decreased surface albedo is particularly strong due to the snow masking effect of the high canopy in late winter/spring. The overall effect on near-surface temperatures varies by season and region, depending, for instance, on snow cover and incoming solar radiation

The overall significance of the effects of re- and afforestation depends on the projected changes in climate in Sweden. Increasing near-surface temperatures are expected to reduce the sequestration rate of carbon in forest ecosystems and, hence, to weaken the cooling effect of afforestation. Reduced precipitation during summer will reduce evapotranspiration and, thus, decrease the fluxes of latent heat and increase the fluxes of sensible heat, weakening the cooling effect of afforestation as well. Warmer near-surface temperatures in winter will reduce the snow cover, amplifying the warming in the winter season as the surface albedo is reduced. At the same time, the snow-masking effect of the canopy becomes less relevant, weakening the warming effect of afforestation in snow-covered areas in late winter and spring.

6. Swedish policy on climate change mitigation

6.1 Goals of the policy

The goals of the Swedish national climate policy (Ett klimatpolitiskt ramverk för Sverige, Regeringens proposition 2016/17:146; Swedish Parliament 2017) are, first, to achieve zero net emissions of GHGs by 2045 and, second, have negative emissions thereafter. The national climate policy foresees sustainably produced bioenergy from forestry as a key enabling factor for the necessary emission reductions in various sectors, e.g. industry, construction, energy and transportation, in Sweden. In a recently published review on sustainable bioenergy in Sweden and other countries, it was noted that today Swedish bioenergy by and large originates from residues from the forest industry, forestry and agriculture (Bioenergi på rätt sätt; Swedish Forest Agency 2017). In order to be sustainable (in accordance with the international standard ISO 13065:2015 for "Sustainability criteria for bioenergy") the production of biomass for energy and other purposes must neither cause deforestation nor reduce the carbon stocks at a landscape scale in any way. Sustainable bioenergy must not reduce biodiversity, weaken the soil's long-term productivity, impair the state of the soil or the water or cause harmful releases of pollutants.

At the request of the Swedish Government, the Swedish Environmental Protection Agency (2018a) formulated a proposal for a long-term strategy of how Sweden could reduce GHG emissions in accordance with the PA (see Chapter 2.2). In particular, the proposal considered legal and policy instruments, i.e. directives, regulations and laws, for various sectors that the government either had already adopted or had announced. The proposal considered various areas of action, i.e. transport, machinery, industry, electricity production and district heating, housing and premises, waste, agriculture and forests. According to the proposal, forests were expected to give important contributions to the storage of carbon and the reduction of GHG emissions and, thus, to the achievement of the goals formulated in the Swedish national climate policy. The proposal focuses on biogeochemical interactions in relation to the sequestration of carbon in forest ecosystems and to avoiding GHG emissions. But the biophysical effects of the changes in land use and land cover associated with the prospective measures are not considered as part of the existing strategy.

The Swedish forestry law (Skogsvårdslagen; Swedish Forest Agency 2019) has two overall equally important goals, i.e. to support production and to protect the environment. The goal related to the production implies that forests and woodlands shall be used effectively and responsibly in order to provide sustainable returns. The goal related to the environment implies that the natural productive capacity of woodlands shall be protected. Furthermore, the biodiversity and the genetic diversity shall be secured. There don't exist any legal or policy instruments specific to the reduction of GHG emissions or the increased storage of carbon in forests or woodlands. Current legislation, however, indirectly does affect developments in the storage or emissions of CO_2 in various ways, mainly through regulations on silviculture in the Swedish forestry law, regulations on ground drainage in the environmental legislation ("Miljöbalken") as well as area protection and wildlife conservation.

6.2 Role of Swedish forests and forestry for climate mitigation

Forestry is important for the Swedish national economy. About 70% of the total land area of 40.8 mio ha (corresponds to 408,000 km^2) of Sweden is covered by forests, i.e. 57% productive and 12% unproductive forested land (Swedish Forest Agency 2015). Half of the productive forested land belongs to individual owners (about 200,000 families), 25% to private-sector companies and 14% to state-owned companies. The forest product industry accounts for 9-12% of the Swedish industry's total employment, exports, sales and added value. According to the Royal Swedish Academy of Agriculture and Forestry, forestry can contribute to the Swedish Government's commitments to reduce GHG emissions both through reduced emissions and through increased carbon sinks (Swedish Forest Agency 2015; the overview on "Forests and Forestry in Sweden" was produced in close cooperation with the Swedish University of Agricultural Sciences, Umeå University, the Swedish Forest Industries Federation, the Federation of Swedish Family Forest Owners, the Swedish Forest Agency and the Forestry Research Institute of Sweden). Active forest management and the use of forest biomass to replace fossil energy and energy-intensive products can create a considerable long-term climate benefit. The conservation of forests and the reduction of harvest rates can also enhance the climate benefit due to increased carbon stocks in forest ecosystems but leads, at the same time, to reduced carbon stocks in harvested wood products. The Royal Swedish Academy anticipates that over time the benefits from substitution can more than compensate for the losses in the carbon stocks in forest ecosystems. In recent years, several studies have investigated the role of forest management and forestry for climate mitigation in Sweden. Several of these studies are reviewed here. We also refer to a special issue on the "Sustainability of increased forest biomass harvest from a Swedish perspective" (De Jong et al. 2017a).

To begin with, it is important to know the demand for biomass that needs to be met from forests for energy purposes and for the substitution of carbon-intensive materials with products from forestry. Börjesson et al. (2017) assessed the potential changes in the demand of forest-based biomass in Sweden in 2030 and 2050, respectively, compared to the current situation. The study included various kinds of demand of energy, i.e. district heating, electricity production in combined heat and power (CHP) production, industrial process energy and production of biofuel for road transportation. Moreover, the potential demand for forest-based feedstock in the chemical and petrochemical sector replacing the current use of fossil feedstock was considered.

Table 6.1 summarises the estimated changes in the demand for forest biomass in different sectors in Sweden. The overall additional demand for forest fuels for energy purposes is estimated at 28-34 terawatt hours (TWh; 1 terawatt is 10^{12} Watt) per year in 2030 and 34-42 TWh/year in 2050, respectively. These increases correspond to 22-26% in 2030 and 26-32% in 2050 with respect to the present-day use. Large increases in the demand are related to biofuels for road transportation and to process energy in the industrial sector. Smaller increases are anticipated for electricity production by CHP, while the demand associated with the heat production for the housing sector is estimated to decrease. There is, however, a new demand of forest biomass for district cooling. The main driver for the growing demand for energy purposes in 2050 is the process energy in the industrial sector, while the demands for the other energy services either decrease or remain unchanged. If the demand for forest biomass as a renewable feedstock in the chemical and petrochemical industry is included, the overall demand increases considerably to 40-47 TWh/year in 2030 and 62-72 TWh/year in 2050, i.e. with an additional 8-10% in 2030 and 12-13% in 2050 with respect to the present-day use. The lower-end values of the estimates in Table 6.1 are based on scenarios with substantial improvements in energy efficiency, combined with greater electrification in all sectors, resulting in reduced demand for forest-based fuel and feedstock. The higher-end values, on the other hand, are based on scenarios with slow improvements in energy efficiency and limited electrification, leading to a larger demand for forest biomass. There is, however, some uncertainty to the estimates presented here due to, among others, the specific choices for the underlying assumptions and differences between data sources used in the study. For the total demand of forest biomass for energy purposes the uncertainty ranges are 12-51 TWh/year in 2030 and 10-64 TWh/year in 2050 (Börjesson et al. 2017). When the demand for the chemical and petrochemical industry is included, the uncertainty ranges are 20-68 TWh/year in 2030 and 30-104 TWh/year in 2050.

Table 6.1: Estimated differences in the demand for forest fuels in different sectors in Sweden in 2030 and 2050, respectively, compared to present-day uses of forest fuels. The range of the estimates relate to different scenarios for improvements in energy efficiency and the progress of electrification in the different sectors. The approximate relative difference with respect to the present-day use of biomass are given in parentheses; units are [%]. Adapted from Börjesson et al. (2017)

		Estimated difference [TW h/year]	
Energy service / carrier	**Sector**	**2030**	**2050**
Heating	District heating	-4 to -3 (-10%)	-6 to -4 (-15 to -10%)
	Individual heating	0	0
Cooling	District cooling	1*	1*
Electricity production	Combined heat and power (CHP) production in district heating	4 to 5 (40 to 50%)	2 to 4 (20 to 40%)
	CHP in industry	2 to 3 (30 to 40%)	2 to 3 (30 to 40%)
Process energy	Industry	7 to 8 (15%)	17 to 18 (30%)
Biofuels	Road transportation	18 to 20 (160 to 180%)	18 to 20 (160 to 180%)
Total energy		28 to 34 (22 to 26%)	34 to 42 (26 to 32%)
Feedstock	Chemical and petrochemical industry	12 to 13*	28 to 30*
Total energy and feedstock		40 to 47 (30 to 36%)	62 to 72 (48 to 55%)

*Insignificant use of biomass today

According to De Jong et al. (2017b), a sustainable supply of forest residues, which is not in conflict with the environmental quality objectives in Sweden, is estimated at 20 TWh/year from final felling. This level can grow to 28 TWh/year, if the potential supply from thinning is included. With a current harvest of forest residues in Sweden between 6 and 10 TWh/year, the potential increase in forest biomass supply then amounts to 10-22 TWh/year. This corresponds to approximately 70% (in 2030) and 55% (in 2050) of the additional demand for forest-based fuel for energy purposes estimated by Börjesson et al. (2017). If the potential demand as feedstock in the chemical and petrochemical industry is also considered, these fractions drop to about 45% for 2030 and 30% for 2050, respectively. In conclusion, the residues from logging would not meet the demand and additional biomass from other sources would be needed.

The supply of forest biomass to substitute fossil energy sources and energy intensive materials, i.e. concrete, aluminium and steel, gives a long-term benefit for climate through a significant reduction of GHG emissions (e.g. Sathre and O'Connnor 2010, Gustavsson et al. 2015), but leads to lower carbon stocks in the forest ecosystems. An appropriate trade-off between the provision of forest biomass and material to replace fossil energy sources and energy intensive materials on one hand, and the storage of carbon on the other, should incorporate the effects of different forest management options on climate and other environmental aspects in an integrated manner.

Furthermore, such an assessment should also incorporate the biophysical effects of the associated changes in land cover on climate.

Gustavsson et al. (2017) undertook such an integrated assessment (not including the biophysical effects, though) to estimate the climate effects of directing forest management in Sweden towards increased carbon storage in forests with more land set-aside for protection vs. towards increased forest production for the substitution of carbon-intensive materials and fossil fuels. Their analysis was based on three different scenarios of forest management and biomass extraction, combined with three different scenarios for building construction and three different scenarios for the energy supply. For forest management, a BAU, a Set-aside and a Production scenario were considered. The BAU scenario reflected current forestry practices, except for the harvest level, which was largely kept at the same level as the growth. In the Set-aside scenario, the protected area was doubled, while it followed the BAU scenario otherwise. In the Production scenario, no extensive or natural regeneration of the forest was assumed, the planting of Pinus sylvestris was replaced by the faster growing Pinus contorta half of the times and the fertilized area was doubled as compared to the BAU scenario. The current value of 8 TWh/year for the harvest level of forest residues from thinning and felling was used as a reference value for all three scenarios. In addition, the study included the cases with an increased harvest of forest residues corresponding to 50% of the slash in thinning and 80% of the slash in final felling. Moreover, for the BAU and Production scenarios the case in which an additional 50% of the stumps in the final felling were harvested was examined. Three different modern wood-based building systems were considered, i.e. cross-laminated timber, beam-and-column and modular building systems. All these wood construction materials were assumed to be produced from large-diameter stems. In the case of the Production scenario, the additional harvest of stems, as compared to the BAU scenario, was used to replace non-wood construction material. In the Set-aside scenario, on the other hand, more non-wood construction material was used due to the reduced availability of stems. As for the energy supply, CHP production was considered, in one case biomass was used to replace coal and in another case to replace gas as fuel. The third case considered the production of liquid motor oil based on biomass (dimethyl-ether), replacing fossil diesel.

In their integrated analysis, Gustavsson et al. (2017) estimated the annual CO_2 emissions (as well as the corresponding cumulative emissions) and the cumulative radiative forcing (CRF) for the various scenarios until the end of the 21st century to give an overall assessment of how the Swedish forest resources can contribute to climate mitigation. The authors estimated CRF using the simplified climate models described in Zetterberg (1993) with parameters updated from AR5.

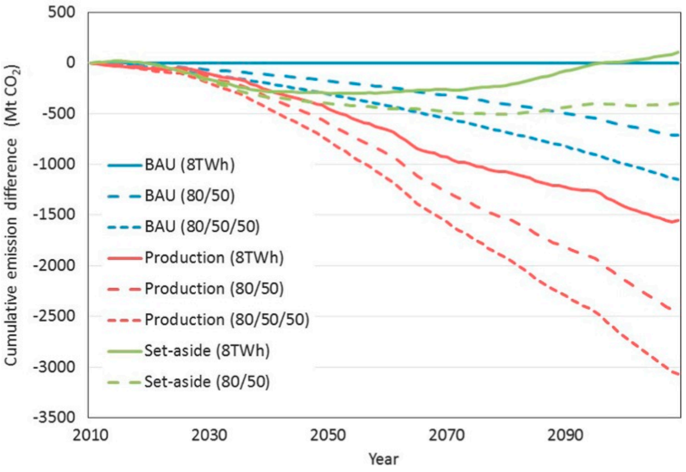


Fig. 6.1: Temporal evolution of the differences in the cumulative CO_2 emissions between various scenarios for forest management and harvest utilization and the BAU reference scenario, using the main energy and building alternatives. From Gustavsson et al. (2017)

Figure 6.1 shows the resulting differences of the cumulative CO_2 emissions for the various forest management and harvest scenarios to the BAU reference scenario. According to this, almost all scenarios are associated with decreased cumulative CO_2 emissions until the end of the century compared to the BAU reference scenario with the current harvest level of forest residue biomass. The only exception is the Set-aside scenario without any change in the harvest level with rather strong cumulative emissions in the second half of the 21st century. The reason is that after an initial increase of the carbon storage in the trees the forest uptake of carbon goes down and the use of carbon intensive materials and of fossil fuels intensifies, leading to an overall increase of the CO_2 emissions. The Production scenario has considerably lower cumulative CO_2 emissions because of the continuing biomass harvest for replacing construction material and fossil fuels in energy production. The figure also illustrates the importance of the harvest level of forest residues for the cumulative emissions. For the Production scenario, for instance, the difference from the reference scenario is twice as large compared to the current harvest level, when 50% of the slash in thinning as well as 80% of the slash and 50% of the stumps in the final felling are harvested.

The CRF is weaker than for the BAU reference scenario for all the scenarios considered in the study (Fig. 6.2), including the Set-aside scenario due to the long residence time of the CO_2 in the atmosphere. The CRF is considerably weaker for the Production than for the Set-aside scenario, and the forcing is also weaker when more forest residue is harvested. In the case of the Production scenario with the current harvest level, the CRF is reduced by about 2 megawatt seconds (MWs) per m^2 at the end of the 21st century without increasing the harvest level and by about 4 MWs/m^2 with the most intense harvesting of forest residues. Similar reductions are associated with the scenarios for building construction and the energy supply. The three alternatives for wood-based building systems lead to a reduced CRF by 4-5 MWs/m^2, with the strongest reduction for the modular building system with pre-fabricated light frames (Gustavsson et al. 2017). The replacement of coal by biomass in CHP production results in a reduction of the CRF by about 4 MWs/m^2, while the replacement of gas by biomass or the production of liquid motor oil based on biomass instead of fossil fuel reduces the CRF by approximately 2 MWs/m^2.

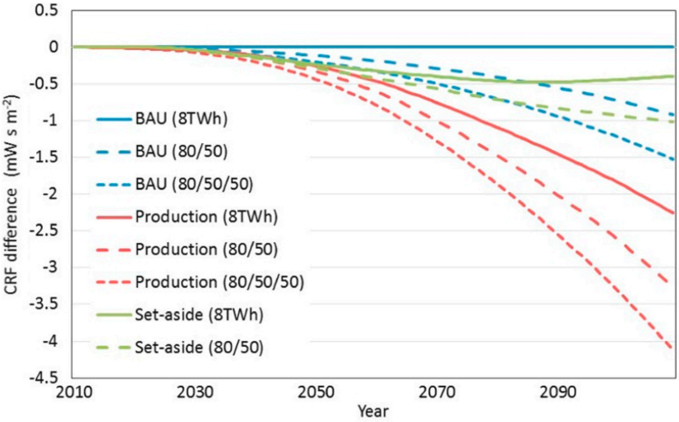


Fig. 6.2: Temporal evolution of the difference in the cumulative radiative forcing between various scenarios for forest management and harvest utilization and the BAU reference scenario, using the main energy and building alternatives. The instantaneous radiative forcing is computed by dividing the cumulative radiative forcing by the number of seconds per year, so that a cumulative radiative forcing of 1 MWs/m^2 corresponds to an instantaneous radiative forcing of approximately 0.032 W/m^2. From Gustavsson et al. (2017)

The results indicate that active forest management and the efficient utilisation of forest products are more beneficial for climate mitigation than setting more land aside for storing carbon in forest ecosystems. However, a strategy aiming at high forest production and harvest, a high rate of residue recovery and a highly efficient utilisation of harvested biomass would not be sustainable in the sense that the carbon stocks in forest ecosystems must not be reduced at landscape scale (see Chapter 6.1).

According to Cintas et al. (2016), the overall climate effect of forest-based bioenergy depends on the specific characteristics of forest ecosystems and forest management (including biomass extraction for bioenergy and other products) as well as on how forest management changes in response to anticipated market demands. Moreover, the climate effect depends on the energy systems, i.e. the extent to which forest biomass replaces fossil fuels for bioenergy and other purposes. The authors also pointed at several relevant issues of sustainable forest management, which have not received much attention so far. These are other ecosystem services of the forest, i.e. the improvement of the air quality, the purification of water, the stabilization of soils or the conservation of biodiversity, and social services such as employment and recreation.

Cintas et al. (2017) investigated the potential role of forest management in relation to the Swedish goal of climate neutrality by the middle of the 21st century in accordance with the PA. Again, forest management is expected to support the storage of carbon in forest ecosystems and to provide biomass for various uses, including energy production. In particular, the authors evaluated the aggregated GHG balance in relation to the 2 °C target and an allocated CO_2 budget for Sweden. The study considered, on one hand, the use of energy for heat, electricity and road transport and, on the other, forest management and production as well as the use of various forest products. The latter includes products for export, with more than 60% of the saw timber and almost 30% of the pulp produced in Sweden that is currently exported. In the assessment, two scenarios for energy use were combined with four different scenarios for forest use. The two energy scenarios describe different developments of the demand of energy in Sweden. One is the BAU scenario, the other the ROADMAP scenario, which broadly aligns with the national goal of GHG neutrality in 2050 (Profu 2012). In the BAU scenario the GHG emissions from fossil fuel remain close to the current level, while they decrease by about 80% in the ROADMAP scenario due to, among others, strongly improved energy efficiency. For the forest use, the REF scenario represents current silvicultural practices and environmental considerations in Swedish forestry. The biomass extraction is relatively low in this scenario, i.e. 15% slash, and, hence, is representative for a situation without any significant initiative to use more biomass for energy production. In the LESSEXPORT scenario, the forest management is similar to the REF scenario, but pulp and paper exports are reduced and substantial volumes of pulpwood are used as biofuel feedstock. Finally, two BIO scenarios represent situations in which more slash is removed and stumps are used for bioenergy. In the BIO1 scenario, forest management is similar to the REF scenario, except the intensified removal of forest residue. In the BIO2 scenario, on the other hand, regeneration efforts are intensified, genetically improved plant material is used and fertilizer is applied, leading to an increased average productivity of about 50% at the end of the 21st century.

In Figure 6.3, the biomass supplies are compared to the biomass demand for the different scenarios. The comparison between the demand for the BAU energy scenario and the supply for the REF scenario for the forest use (left panel) reveals that in this case the current forest management with an extraction level of 15% of the slash at the final felling is not sufficient to meet the demand for biomass. Up to 2030, there is enough forest biomass provided to meet the demand in all sectors except the transportation sector, but after 2030 the demand in the other sectors cannot be fully met either. As for the ROADMAP energy scenario (right panel), the BIO1 forest use scenario is sufficient to meet the biomass demand in the near future, but in the period

2030-2050 the total demand is higher. The biomass supplies in BIO2, however, exceeds the demand associated with the ROADMAP scenario through the entire first half of the 21st century. This excess of forest biomass could be used for other purposes, e.g. as feedstock in the chemical and the petrochemical industries. In the LESSEXPORT scenario (not shown in the figure), 15% of the forest biomass, which no longer is exported, can be used to cover the total demand of biofuels for transportation instead.

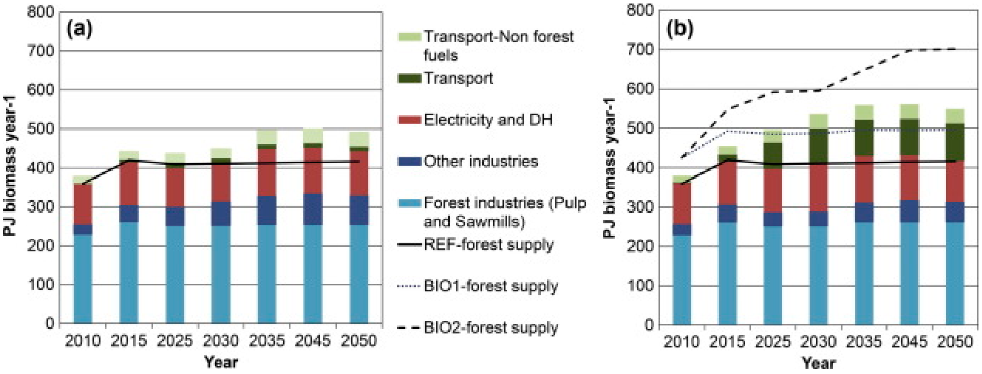


Fig. 6.3: Comparison between forest biomass supply (black lines) and biomass demand for energy. (a) REF supply compared with BAU demand. (b) REF, BIO1, and BIO2 supplies compared with ROADMAP demand. The bioenergy demand is disaggregated into: Forest industries including sawmills and pulpmills; Other industries (includes residential and services); Electricity and district heating (DH); Transport sector (road, aviation, and shipping). Transport sector demand is divided into demand for biofuels based on forest biomass and on other feedstocks. From Cintas et al. (2017)

All ROADMAP scenarios are associated with negative GHG emissions for Sweden at the middle of the 21st century, regardless of the scenario for forest use (Fig. 6.4). As the emissions from fossil fuels decrease, the sequestration of carbon in the forests and in forest products becomes more important, leading to negative net emissions for Sweden at some point in time. The negative emissions for Sweden were estimated at about 10 Mt CO_2-eq/year for all three scenarios. When the contribution of the Swedish forest sector to the reduction of the GHG emissions in the world is fully considered, the magnitude of the negative emissions is much larger, i.e. about 35 Mt CO_2-eq/year for the BIO1 (upper panel) and the LESSEXPOERT scenario (lower panel) and 50 Mt CO_2-eq/year for BIO2 (middle panel). The strong negative emissions in the case of BIO2 occur because the measures to enhance forest growth result in a higher storage rate of carbon in forest ecosystems and allow for the intensified production of saw wood and biofuel. The fact that the magnitudes of the net GHG emissions differ only slightly between the BIO1 and the LESSEXPORT scenario illustrates that the underlying assumptions for each of the scenarios have a similar effect on the GHG emissions; i.e.

either increasing the level of biofuel production by enhancing the extraction of forest residues (BIO1) or reducing the paper production and using some of the pulpwood as biofuel feedstock instead (LESSEXPORT).

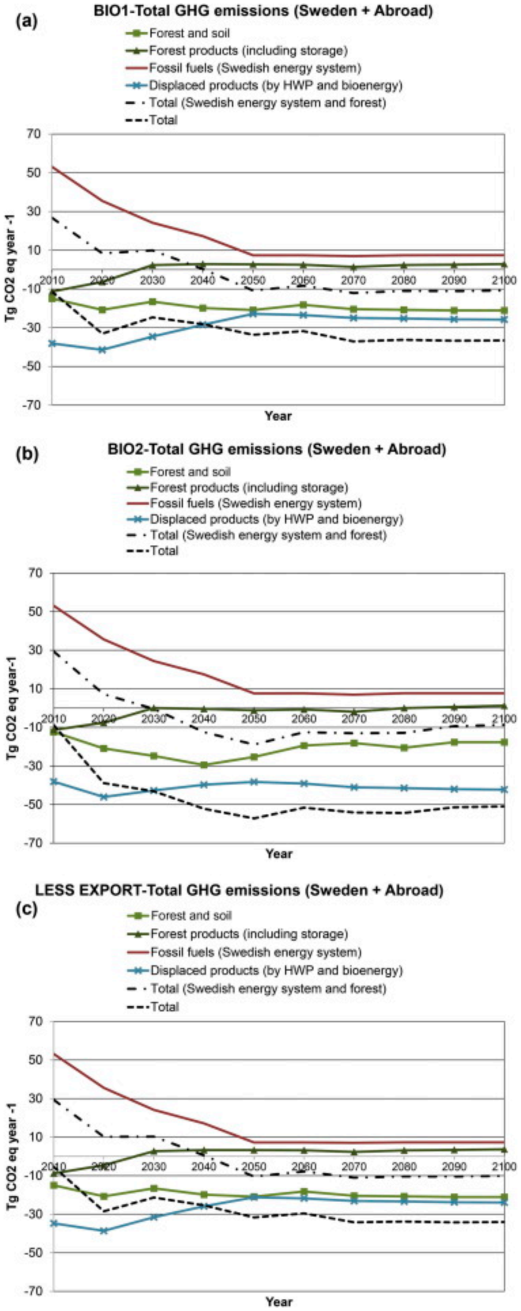


Fig. 6.4: Net greenhouse gas (GHG) emissions in Sweden with and without considering effects of forest product export. (a) BIO1-ROADMAP; (b) BIO2-ROADMAP; (c) LESS EXPORT-ROADMAP. Fossil fuels refers to emissions from the Swedish energy system; Displaced products refers to GHG savings due to product displacement abroad, both harvested wood products (HWP) and bioenergy; Total (Swedish energy system and forest) excludes displacement effects abroad, which are included in Total. From Cintas et al. (2017)

Lundmark et al. (2014) used three very similar scenarios for forest management, the harvest of biomass and the biomass use in Sweden to analyse their effects on CO_2 emissions and removals until the end of the 21st century. For the baseline scenario (BAS) the authors found avoided CO_2 emissions over the entire period of simulation (1990-2105), both in Sweden and abroad. In Sweden the accumulated avoided emissions over that period were estimated at 2.8 Gt CO_2-eq and at 4.9 Gt CO_2-eq abroad. Abroad equally strong contribution to the removals were associated with material substitution (excluding pulp and paper) and energy substitution. In Sweden, on the other hand, carbon sequestration in forest ecosystems largely contributed to the removals in combination with energy substitution. This removal was to some extent offset by additional CO_2 emissions related to material substitution with pulp and paper. The stronger removals abroad are related to the high share of exported wood products from Sweden and the higher substitution effect abroad. For the two scenarios with higher biomass yields the climate benefits from reduced CO_2 emissions were larger, in particular when also forest growth was increased (BAS-G). The global effect, combing the removals in Sweden and abroad, added up to accumulated avoided emissions of 8.2 Gt CO_2-eq for the scenario with increased harvest (BAS-H) and 11.2 Gt CO_2-eq for BAS-G compared to 7.7 Gt CO_2-eq for BAS. Based on their results, the authors concluded that the effects of both forest production and the trade of wood products are important for the overall climate benefit. To optimize the CO_2 balance in Sweden, wood resources should be used for solid wood products or energy production rather than for pulp and paper production. From a global perspective (and in the long-term), the effects of material and energy substitution appeared to be much more important than carbon sequestration in Sweden.

7. Engagement with stakeholders

7.1 Affected sectors and policymakers

On September 17, 2018, we organized a workshop with representatives from various sectors and areas that most likely are affected by the national climate policy, i.e. forest industry, forestry and agriculture, natural resource management and nature conservation. The workshop was centred on bioenergy, and the recent report on the sustainable production of bioenergy (Bioenergi på rätt sätt; Swedish Forest Agency 2017) was presented (see Chapter 6.1). The majority of the participants are part of the stakeholder reference group from the two strategic research areas "Biodiversity and Ecosystem Services in a Changing Climate" (BECC; see http://www.becc.lu.se) and MERGE (see Chapter 4.2), both hosted by the Centre for Environmental and Climate Research (CEC) at Lund University (LU). BECC is s collaboration between LU and the University of Gothenburg (UGOT), with several departments from each university participating, i.e. seven at LU and three at UGOT. MERGE is a collaboration between several universities, i.e. LU, UGOT, the Chalmers University of Technology, the Royal Institute of Technology and the Linnaeus University, and SMHI. Similar to BECC, LU has participants from five departments and UGOT from three. Several scientists from these two research areas participated in the workshop (see Table 7.1 for details). Various relevant institutions, agencies and organizations were represented at the workshop by individuals, e.g. Sveaskog, the Swedish Forest Agency, the Swedish Board of Agriculture, the Swedish Environmental Protection Agency or the Swedish Society for Nature Conservation (see Table 7.2 for details).

Table 7.1: The scientists from the BECC and MERGE strategic research areas participating in the workshop on September 17, 2018

Name	**Institution**	**Research area**	**Research interests**
Cecilia Akselsson	Department of Physical Geography and Ecosystem Science, Lund University	BECC	Natural sciences, environmental sciences, forest systems, ecosystem services
Yann Clough	Centre for Environmental and Climate Research, Lund University	BECC	Agricultural sciences, environmental sciences, landscape ecology, ecosystem services, land use
Marianne Hall	Centre for Environmental and Climate Research, Lund University		Environmental sciences, climate change, land use
Mattias Hallquist	Department of Chemistry and Molecular Biology, University of Gothenburg	MERGE	Atmospheric sciences, atmospheric chemistry, particle emissions
Åsa Kasimir	Department of Earth Sciences, University of Gothenburg	BECC	Natural sciences, environmental sciences, greenhouse gas emissions, land use
Wilhelm May	Centre for Environmental and Climate Research, Lund University	MERGE	Atmospheric sciences, climate research, climate change, land surface processes
Paul Miller	Department of Physical Geography and Ecosystem Science, Lund University	MERGE	Natural sciences, climate research, terrestrial carbon cycle, vegetation dynamics
Johanna Alkan Olsson	Centre for Environmental and Climate Research, Lund University	BECC	Social sciences, environmental sciences, processes of social change, stakeholder interaction
Håkan Pleijel	Department of Biological and Environmental Sciences, University of Gothenburg	BECC	Environmental sciences, air pollution, agriculture, vegetation
Henrik Smith	Centre for Environmental and Climate Research, Lund University	BECC	Environmental sciences, ecology, biodiversity, conservation biology, ecosystem services

Table 7.2: The stakeholders participating in the workshop on September 17, 2018

Name	**Organisation**	**Sector**
Tomas Björnsson	Swedish Society for Nature Conservation (Naturskyddsföreningen)	Nature conservation
Per Bodin	Swedish Board of Agriculture (Jordbruksverket)	Agriculture
Måns Bruun	Skåne County Administrative Board (Länsstyrelsen Skåne)	Natural resources
Annie Drottberger*	Federation of Swedish Farmers (Landbrukarnas Riksförbund)	Agriculture
Hillevi Eriksson	Swedish Forest Agency (Skogsstyrelsen)	Forestry
Olof Johansson	Sveaskog	Forest industry
Ola Inghe	Swedish Environmental Protection Agency (Naturvårdsverket)	Natural resources
Kajsa Pira	Air Pollution and Climate Secretariat	Environment
Helen Rosengren*	Federation of Swedish Farmers (Landbrukarnas Riksförbund)	Agriculture

*via link

At the workshop, three main questions relevant for the subject of the synthesis were addressed, namely:

- How does the new Swedish climate policy and goals affect decisions concerning Swedish agriculture and forestry?
- How will and should the instruments that influence the decisions on land use in Swedish agriculture and forestry evolve? What effects can be expected regarding biodiversity, ecosystem services and climate impacts?
- How should one consider other climate impacts than the effects caused by greenhouse gases in the decisions on land use?

The workshop was divided into two parts. In the first part, Hillevi Eriksson, climate and bioenergy specialist at the Swedish Forest Agency presented the report “Bioenergi på rätt sätt”, adding some perspectives related to relevant research to it. In the second part, the workshop participants discussed the three main questions.

It is important to note that the aforementioned report was a collaborative effort between four different national agencies and the counties’ administrative boards and, thus, combines input from stakeholders with different specific interests. The agencies involved were the Swedish Forest Agency, the Swedish Board for Agriculture, the Swedish Environmental Protection Agency and the Swedish Energy Agency. Three of the agencies were represented at the workshop, the Swedish Energy Agency was missing.

According to Hillevi Eriksson, it is a challenge to translate scientific results into useful guidelines that consider climate and other sustainability issues in society. Much of the research on the effects of bioenergy on land use and climate is too specific to feed into the development of guidelines. Studies often only address certain specific effects but omit others and, thus, provide a fragmented picture of the state of knowledge that is difficult to use as a basis for decision-making. Several research questions would need to be addressed to guide policy development on the role of bioenergy in Sweden:

- How is climate policy controlled and shaped in the European Union?
- How does the production of bioenergy compete with the demand for food? What does affect the risk of more expensive food prices associated with intensified production of bioenergy?
- How can a fully sustainable production of bioenergy in agriculture and forestry be achieved?
- How can bioenergy be produced in forests in accordance with environmental protection?
- Which incentives might make forest owners work for higher carbon storage?

The main purpose of the plenary discussion was to bring about different views on the three main questions described above by the workshop participants. Therefore, the following summary of the discussion is primarily a collection of the (subjective) views of individual researchers and the representatives from different sectors, national agencies for resource management and organisations for nature conservation. Guided by the three main questions, the discussion developed around five different aspects of bioenergy, i.e. the climate targets, legal and policy instruments, forestry, agriculture and the landscape level. For the purpose of this synthesis, the aspects of forestry and of legal and policy instruments ("styrmedel") were of particular relevance. In the following, therefore, a collection of the views regarding these two aspects is presented.

Forestry sector:

- Forests in Sweden are influenced by numerous interests and needs, so that it might be necessary to develop new legal and policy instruments. Traditional/established Swedish forestry practices may not be suitable in the future.
- The forestry industry has noticed a reduction in the usage of tops and branches for bioenergy in recent years. At the same time, the usage of residues from forest industry to replace fossil fuels has increased.
- There is a conflict between environmental protection and the removal of biomass in forests for bioenergy. From the environmental point of view, leaving more dead wood would be desirable, while taking out biomass often leads to a removal of dead wood.
- It is important to investigate, whether it would be good to have forests with different levels of protection, i.e. how much protection can be achieved by different regulations and legal instruments and what effects might this have for the biological diversity?
- Additional knowledge on the environmental effects of thinning before the final felling is needed.
- The forest industry considers the Swedish national climate policy as very ambitious. Fulfilling its goals will require the intensified use of forest products. To optimize the climate effects, bioenergy should be produced nationally.
- The forest industry sees an urgent need for legal and policy instruments for the use of forests. Moreover, it is essential to analyse, how research can contribute to the implementation of such instruments.
- It is important to address both the needs of the big commercial forest industry and the needs of small family-owned enterprises.
- To begin with, the forest industry would need knowledge on the impacts of specific types of forest management, providing a basis for decisions on the management.

Legal and policy instruments:

- The governance of Swedish climate policy is complex, with different sustainability goals and various actors, having different assignments and different approaches.

- There are conflicts between the assignments of the different actors as well as between the effects of various measures implemented in the agriculture and forestry sectors and for nature conservation.
- The scientific assessments of the potential for biofuel production and the effects of the increased use of bioenergy are based on a variety of conditions, but these specific conditions are not always followed up or taken into account when designing policies and policy instruments.
- There is also a need to follow up and further investigate the effects of existing instruments. Various kinds of measures are adopted, but it is not always clear which effects these measures have.

7.2 Scientific stakeholders

Overall, Sweden holds the capacity and capability needed to extend the utility and to overcome the limitations of the available modelling tools for assessing the biophysical (as well as the biogeochemical effects) of anthropogenic LULCC. This is, not at least, documented through a list of national and international research projects, addressing related research question, and the MERGE strategic research area (see above).

SMHI (http://www.smhi.se) is the leading Swedish institution in the field of regional climate modelling. In addition, SMHI plays an important role in the EC-Earth consortium (http://www.ec-earth.org), where a community ESM, EC-Earth, has been developed by numerous research centres and universities in Europe. SMHI and LU, i.e. the Department of Physical Geography and CEC, have closely collaborated on the development of RCA-GUESS (Smith et al. 2011; see Chapter 4.2) and on including the LPJ-GUESS terrestrial ecosystem model (see Chapter 4.2) into EC-Earth. Many of the recent developments in LPJ-GUESS (see Chapter 4.3) have already been considered in version 3 of EC-Earth in the preparation of CMIP6, but some recent extensions and improvements have not yet. Other developments such as a stronger coupling between the physical land-surface model and LPJ-GUESS still need to be worked out in the coming years. Another line of work is to incorporate BVOC into EC-Earth and to improve the representation of the relevant aerosol processes in the climate model. For RCA-GUESS, there is a need to include several of the recent advances of LPJ-GUESS into the RESM.

In recent years, SMHI has contributed to the development of a new RCM on the basis of the HARMONIE regional model for numerical weather prediction (Lindstedt et al. 2015). In contrast to RCA, the new RCM is particularly suited for simulations at a horizontal resolution of several to tens of km, enabling the model to represent processes, especially convection, and feedbacks at rather small spatial scales. Lindstedt et al. (2015) performed two simulations with the climate version of HARMONIE over Europe under present-day climate conditions, one at a horizontal resolution of 15 km and one at a horizontal resolution of 6 km. The authors evaluated the quality of these simulations against standard observational data sets over Europe as well as high-resolution observations for particular sub-regions. The characteristics of the mean regional climate were very well represented in this RCM, but also higher-order climate statistics (i.e. variability and extremes) and small-scale characteristics of daily precipitation were in good agreement with observations. Just recently, the HCLIM regional climate model has been published, with different configurations of the HARMONIE regional model for numerical weather prediction depending on the horizontal resolution (Belušić et al. 2020).

Building on the fruitful collaboration on RCA-GUESS, SMHI and LU support the idea of interactively coupling the HARMONIE RCM with LPJ-GUESS to design a new RESM. Given the improved simulation of various aspects of climate as compared to the RCA RCM and various and continuous updates to LPJ-GUESS since the first studies using RCA-GUESS were published, including some additional processes and improving the representation of others, a new RESM based on the latest version of LPJ-GUESS and HCLIM would enable a more realistic simulation of the interactions between the atmosphere and the land surface. In particular, such a model could enable simulations of the feedbacks between the land-surface and the atmosphere at a landscape level, as both model components are suitable for very fine horizontal resolutions.

8. Land-use and land-cover scenarios for Sweden

8.1 Shared socio-economic pathways

At the beginning of the decade, the development of a new scenario framework for climate change research was initiated. The vision was to combine pathways of future radiative forcing (Moss et al. 2010) and their associated climate changes with alternative pathways of socioeconomic development as a basis for research on climate change impacts, adaptation and mitigation. O'Neill et al. (2014) proposed the concept of SSPs for use within the scenario framework. The SSPs are defined as reference pathways describing alternative plausible trends in the evolution of society and ecosystems over the 21st century, in the absence of climate change or climate policies. For this, the concept of a space of challenges to adaptation and mitigation that is spanned out by the SSPs is introduced (see Fig. 8.1). Following up on the concept of SSPs, Van Vuuren et al. (2014) introduced a scenario matrix structure to underlie the new scenario framework (see Figure 1 in Van Vuuren et al. 2014). The two main axes of the matrix are the level of RF of the climate system (as characterised by the RCPs) and a set of plausible trajectories of future global development according to the SSPs. It is important to note that not all of the cells can be filled as not all combinations of climate forcing and SSP are feasible (Riahi et al. 2017).

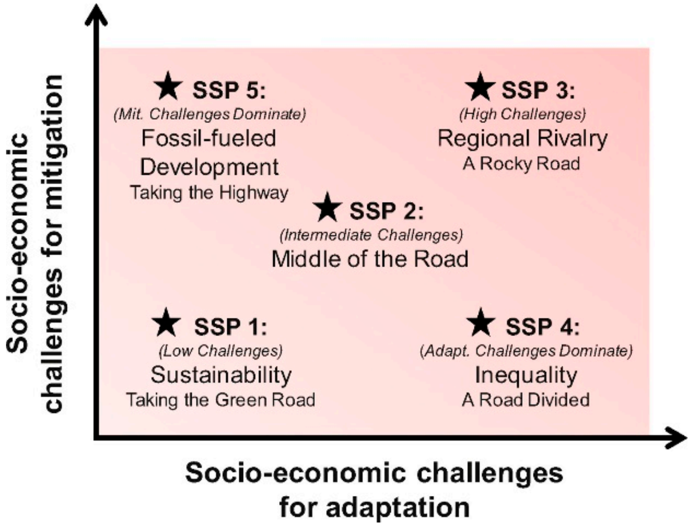


Fig. 8.1: The five shared socioeconomic pathways (SSPs) representing different combinations of challenges to mitigation and adaptation. From O'Neill et al. (2017)

O'Neill et al. (2017) formulated the narratives of the SSPs, giving a set of five qualitative descriptions of future changes in demographics, human development, economy and lifestyle, policies and institutions, technology as well as environment and natural resources. These narratives are intended as descriptions of plausible future conditions at the level of large regions of the globe as a basis for integrated scenarios of emissions and land use. Five narratives have been developed to occupy each of the domains in the challenge space (Fig. 8.1), namely:

In SSP1 (Sustainability – Taking the green road), the world shifts gradually towards a more sustainable path. The combination of directed development and environmentally friendly technologies, a favourable outlook for renewable energy, institutions that can facilitate international cooperation and relatively low energy demand results in low challenges to mitigation. At the same time, the improvements in human well-being, along with strong and flexible global, regional and national institutions imply low challenges to adaptation (lower left corner in Fig. 8.1).

In SSP2 (Middle of the road), the world follows a path on which social, economic and technological trends follow the historical patterns. Development and income growth proceed unevenly, leaving some countries behind expectations. As inequality in income persists or improves only slowly, societal stratification continues and social cohesion is limited, challenges to reduce vulnerability to societal and environmental changes endure and significant advances in sustainable development are constrained. Overall, the moderate development trends make the world face moderate challenges to both mitigation and adaptation, but with considerable variations between and within countries (centre in Fig. 8.1).

In SSP3 (Regional rivalry – A rocky road), resurgent nationalism, concerns about competitiveness and security as well as regional conflict push countries to increasingly focus on national or, at most, regional issues. Few, relatively weak, global institutions reinforce this trend. Growing resource intensity and dependency on fossil fuels, along with difficulties in achieving international cooperation and slow technological changes, mean high challenges to mitigation. The limited progress on human development, the slow income growth and the lack of efficient institutions, imply high challenges to adaptation for many groups in all regions (upper right corner in Fig. 8.1).

In SSP4 (Inequality – A road divided), highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. The combination of some development of low carbon supply options and expertise as well as a well-integrated business class capable of acting quickly and decisively implies low challenges to mitigation. Challenges to adaptation are high for the large proportions of people at low levels of development and with limited access to effective institutions for coping with economic or environmental stresses (lower right corner in Fig. 8.1).

In SSP5 (Fossil-fuelled development – Taking the highway), the world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. The strong reliance on fossil fuels and the lack of global environmental concern result in potentially high challenges to mitigation. The attainment of human development goals, robust economic growth and highly engineered infrastructure lead to relatively low challenges to adaptation to potential climate changes for all but a few (upper left corner in Fig. 8.1).

Riahi et al. (2017) give an overview on the SSPs, including their implications for energy systems, land use and GHG emissions. IAMs were used to develop quantitative scenarios in line with each SSP narrative. For this, the narratives were translated into quantitative projections for main socioeconomic drivers, i.e. population, economic activity and urbanization. Both the narratives and the associated projections of the socioeconomic drivers were elaborated using a range of different IAMs in order to derive quantitative projections of energy, land use and GHG emissions associated with the SSPs. Using a number of different models for the quantitative projections of economic growth and for the integrated energy, land use and emission scenarios in each IAM led to alternative interpretations of each of the SSPs. For each SSP, a marker SSP was selected among the different interpretations as a representative of the overall developments of the respective SSP. The selection of these markers was guided by two main concerns, i.e. the internal consistency of the complete set of SSP markers and the ability of the different models to represent distinct characteristics of the storylines.

Overall, six IAMs provided a total of more than 100 scenarios for different SSPs and five of them were chosen as marker SSPs. These are IMAGE for SSP1 (Van Vuuren et al. 2017), MESSAGE-GLOBIOM for SSP2 (Fricko et al. 2017), AIM/CGE for SSP3 (Fujimori et al. 2017), GCAM for SSP4 (Calvi et al. 2017) and REMIND-MAgPIE for SSP5 (Kriegler et al. 2017).

In these more than 100 baseline scenarios, neither the impacts of climate change for society and ecosystems nor the implications of climate policies (i.e. mitigation) are considered. These baseline scenarios are used as starting points for the development of mitigation scenarios. As long-term targets for the mitigation efforts, the nominal forcing levels of 2.6, 4.5 and 6.0 W/m^2 in 2100 from the RCPs are set. In addition, mitigation runs for a target of 3.4 W/m^2 are included. This intermediate level of RF is placed between very stringent efforts to reduce emissions given in RCP2.6 and the less stringent mitigation efforts associated with RCP4.5. In total, the six IAMs provided more than 80 mitigation scenarios, including a number of marker scenarios using the same models as for the baseline SSPs, i.e. SSP1-2.6, SSP4-3.4, SSP2-4.5 and SSP4-6.0. In addition, a medium- to high-range forcing marker scenario with a RF of 7.0 W/m^2 in 2100 (SSP3-7.0) and a high-range marker scenario with 8.5 W/m^2 (SSP5-8.5) were developed as community scenarios (e.g. O'Neill et al. 2016).

8.2 Community scenarios

The different SSPs are associated with different futures of land use, both for the baseline and the mitigation scenarios (Popp et al. 2017). In the SSP scenarios, six factors affecting land use are considered, i.e. land-use change regulation, land-productivity growth, the environmental impact of food consumption, international trade, globalization and land-based mitigation policies. Table 8.1 gives the specifications for the two factors that are directly related to the subject of this synthesis, i.e. land-use change regulation and land-based mitigation policies, for the five SSPs. As for the land-use change, the degree of regulations varies considerably across the SSPs, ranging from strong regulation (SSP1), high regulation in high- and medium income countries (SSP4) over medium regulation (SSP2, SSP5) to limited regulation (SSP3). The degree of regulation particularly affects the extent of deforestation, with continued deforestation for SSP3 and high deforestation rates for SSP4. Similarly, the speed of international cooperation on climate mitigation and the extent to which the land-use sector participates in mitigation efforts varies strongly, ranging from full participation (SSP1, SSP5) over partial participation (SSP2, SSP4) to limited participation (SSP3).

Table 8.1: Two factors affecting land use for the five shared socioeconomic pathways (SSPs). The World Bank definition for low-income (LICs), medium-income (MICs) and high-income countries (HICs) is used. Adapted from Popp et al. (2017)

Socioeconomic pathway	**Land-use change regulation**	**Land-based mitigation policies**
SSP1	Strong regulation to avoid environmental trade-offs	No delay in international cooperation for climate change mitigation. Full participation of the land-use sector
SSP2	Medium regulation; slow decline in the rate of deforestation	Delayed international cooperation for climate change mitigation. Partial participation of the land-use sector
SSP3	Limited regulation; continued deforestation	Heavily delayed international cooperation for climate change mitigation. Limited participation of the land-use sector
SSP4	Highly regulated in MICs and HICs; lack of regulation in LICs lead to high deforestation rates	No delay in international cooperation for climate change mitigation. Partial participation of the land-use sector
SSP5	Medium regulation; slow decline in the rate of deforestation	Delayed international cooperation for climate change mitigation. Full participation of the land-use sector

In response to these strong variations between the SSP scenario (see Table 1 in Popp et al. 2017 for details on the other four factors), with SSP1 and SSP3 as the most extreme cases and the other three SSPs somewhere in between, the future land-use scenarios (i.e. the baseline scenarios) cover a wide range (Fig. 8.2). In the course of the century, the different land-use types can expand or shrink by hundreds of millions of hectares at a global scale. SSP3, with a massive growth of population, relatively low agricultural production and little emphasis on environmental protection, puts large pressure on global land use. Cropland and pasture are massively expanded at the expense of forests and other natural lands. In contrast, SSP1, featuring a sustainable land transformation, puts relatively little pressure on global land use due to low population projections, healthy diets and limited food waste as well as high agricultural productivity. This scenario indicates a gradual continuous expansion of forests and other natural land (a reversal of the historical trend), along with a reduction of pasture and no change to cropland areas. The other SSP scenarios feature modest changes in land use, with a tendency of an expansion of cultivated land (cropland and pasture combined). The figure also illustrates the wide range of scenarios for the same SSP, provided by the different IAMs. The differences between the models result from a combination of different model philosophies and architectures, inherent uncertainties on the modelled processes and differences on how to parameterize these processes along the various SSPs.

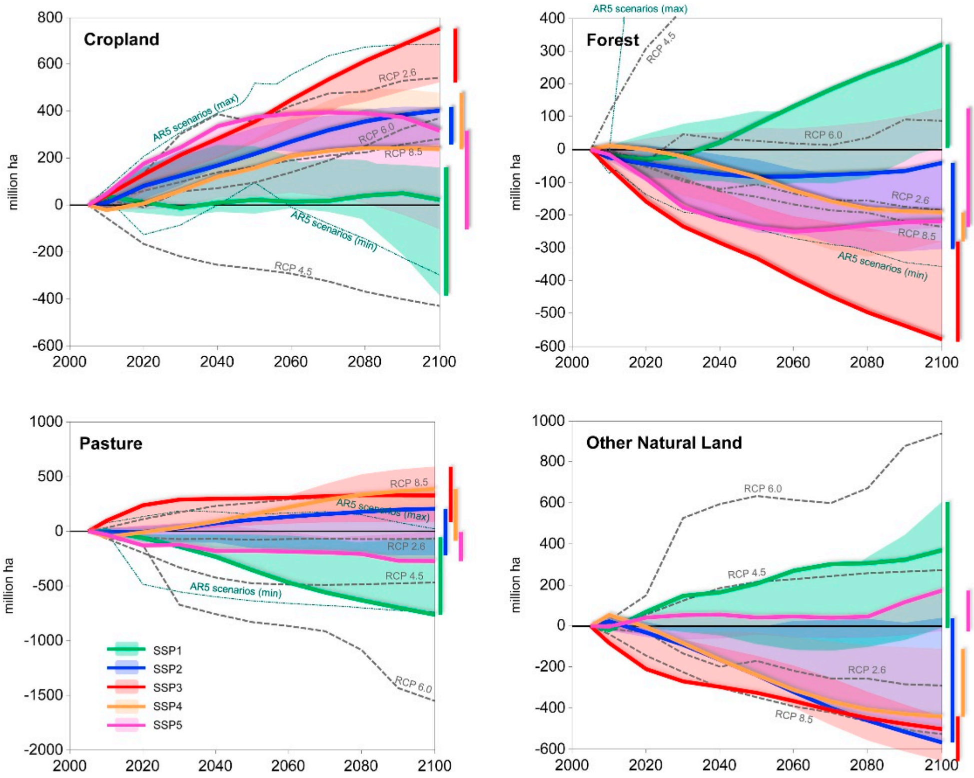


Fig. 8.2: Changes in cropland, forest, pasture and other natural land for the SSP marker baseline scenarios (thick lines) and ranges of other non-marker scenarios (coloured areas). Changes are shown relative to the base year of 2010 = 0. Note that cropland includes energy crops. Other natural land includes all land-categories beyond forests, pasture, cropland, and build-up areas. From Riahi et al. (2017)

The inclusion of mitigation efforts further affects global land use, in particular for the most ambitious mitigation scenarios for RCP2.6. For all SSPs (except SSP3, for which such a weak RF cannot be reached because of major implementation barriers), the area used for energy crops is expanded, in correspondence with the magnitude of the challenges for mitigation and adaptation, respectively. For the marker scenarios, the area used for bioenergy crops range between about 200 mio ha (corresponds to 2 mio km^2) for SSP1 and about 1500 mio ha for SSP4 by the end of the century (see Fig. 3 in Popp et al. 2017). For SSP2 and SSP5, these areas are approximately 600 and 900 mio ha, respectively. For all SSPs except SSP4, considerable fractions of these areas have been transformed from pastures. Also for RCP4.5, the areas for energy crops are expanded for all SSPs except SSP1, but to a much lesser extent. In particular, these areas are roughly the same for the four respective marker scenarios.

For SSP2 and SSP4, large areas of other natural land are transformed into areas for energy crops (Fig. 8.3). For RCP2.6, these are almost 1000 mio ha for the SSP4 marker scenario and about 200 mio ha for SSP2. Also avoided deforestation and, in particular, afforestation contribute to climate change mitigation at the expense of cultivated or other natural lands. For RCP2.6, the forest area is expanded by about 500 mio ha for both SSP1 and SSP2. For RCP4.5, the expansion of the forest area is halved for SSP2 but only slightly reduced for SSP1. The latter is related to the fact that for SSP1 the forest area also increases markedly in the baseline scenario. The forest area is also expanded for SSP4 but decreased for SSP3. Similar to the baseline scenarios, the figure also illustrates the wide range of scenarios for the same SSPs when mitigation is included.

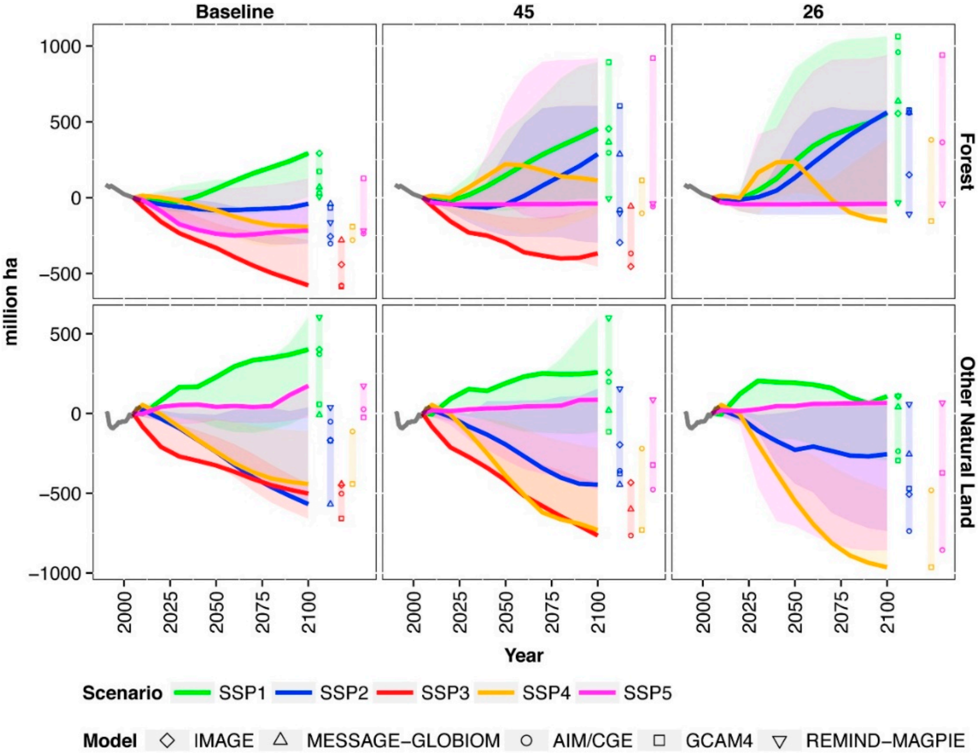


Fig. 8.3: Change in global land for forest (upper row) and other natural land (lower row) of the five SSP marker scenarios for the baseline (left column), RCP4.5 (middle column) and RCP2.6 (right column) cases. Coloured lines indicate the marker model results for each SSP. Coloured bars indicate the range of data in 2100 across all marker and non-marker projections for each SSP (models are depicted by icon). Grey line shows historical trends based on FAO data. From Popp et al. (2017)

Similar to the RCP scenarios (Hurtt el al. 2011; see Chapter 2.6), the University of Maryland produced harmonized land-use scenarios for the mitigation scenarios based on the SSPs, referred to as the LUH2 dataset (University of Maryland 2017a, 2018). The LUH2 data are available for the six marker (mitigation) scenarios for the SSPs for the period 2015-2100, i.e. SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP4-3.4, SSP4-6.0 and SSP5-8.5 (see Chapter 8.1). The LUH2 data have been obtained using essentially the same methodology as for the LUH data, with the same advantages and shortcomings (see Chapter 2.6). The LUH2 data cover 12 possible land-use states, including the separations of primary and secondary natural vegetation into forest and non-forest sub-types, of pasture into managed pasture and rangeland and of cropland into multiple crop functional types (University of Maryland 2017b). There are more than 100 possible transitions between these land-use states and 21 management layers for agriculture and forestry, including irrigation, synthetic nitrogen fertilizer and biofuel management.

Table 8.2: The 12 land-use states from LUH2 (University of Maryland 1017a, 2018)

Acronym	**Land-use state**
urban	Urban land
c3ann	C3 annual crops
c3per	C3 perennial crops
c3nfx	C3 nitrogen-fixing crops
c4ann	C4 annual crops
c4per	C4 perennial crops
pastr	Managed pasture
range	Rangeland
secdn	Potentially non-forested secondary land
secdf	Potentially forested secondary land
primn	Non-forested primary land
primf	Forested primary land

Table 8.3: The five types of wood harvest from LUH2 (University of Maryland 2017a, 2018). Note that the extension "_harv" is not used in Figs. 8.12 – 8.15

Acronym	**Types of wood harvest**
primf_harv	Wood harvest from primary forest
primn_harv	Wood harvest from primary non-forest
secmf_harv	Wood harvest from secondary mature forest
secyf_harv	Wood harvest from secondary young forest
Secnf_harv	Wood harvest from secondary non-forest

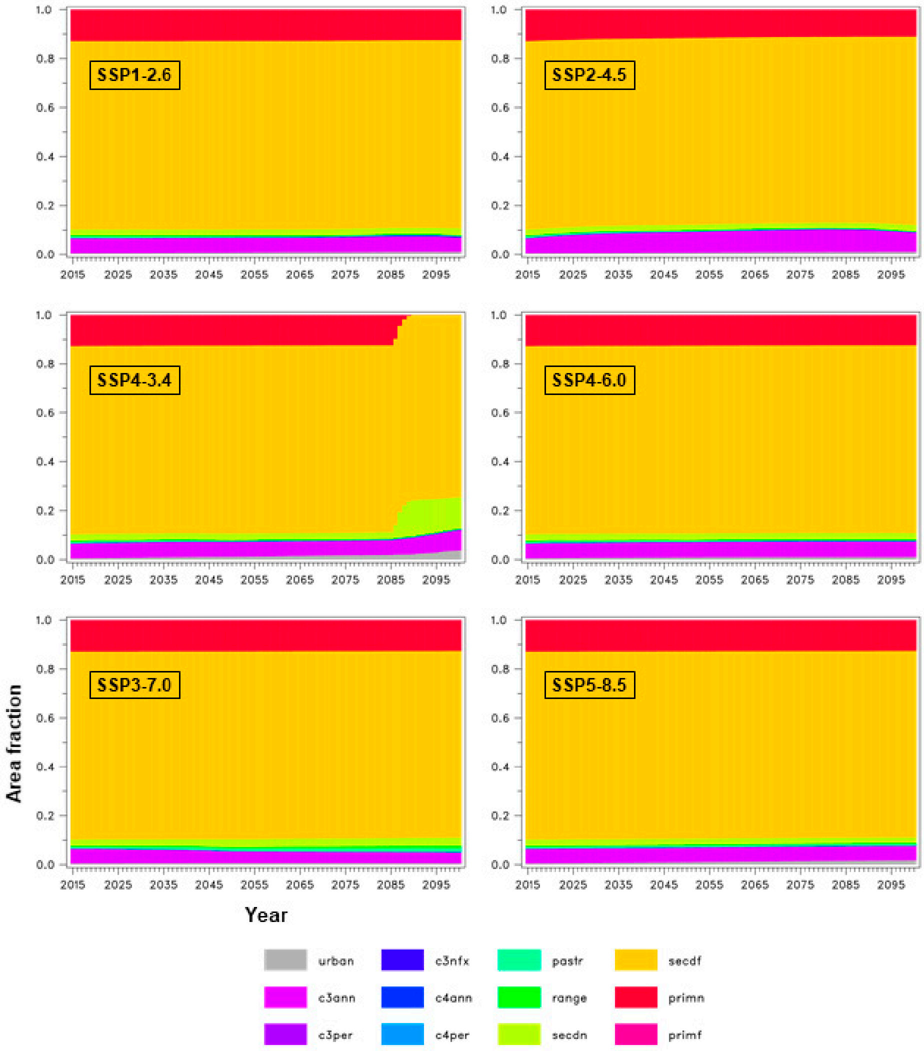


Fig. 8.4: Temporal evolution (from 2015 to 2100) of the fractions of Sweden covered with 12 different land-use states, i.e. urban land, C3 annual, perennial and nitrogen-fixing crops, C4 annual and perennial crops, managed pasture, rangeland, potentially non-forested and forested secondary land as well as non-forested and forested primary land (see Table 8.2 for acronyms), for six different SSP-scenarios from the LUH2 data set (University of Maryland 2017b)

Figure 8.4 shows the temporal evolution of the area fractions of Sweden covered by the 12 land-use states (see Table 8.2 for an overview) from the LUH2 data for the six different SSP scenarios. The area fractions include all grid points defined as Swedish (1402 in total; each covering about 180 km^2), also considering the extent to which a particular grid point is covered by water or ice. According to these data, about three quarters of the Swedish land area is today covered with secondary forest. Other prominent land types are non-forested primary land and C3 annual crops. Forested primary land and C4 annual crops, on the other hand, are not found in Sweden at all. Small fractions of the country are covered by the remaining crop types (C3 and C4 perennial crops) as well as managed pasture, rangeland and urban land. The overall distribution between the main land types does not vary much during the course of the 21st century, except for some shifts between the different crop functional types and/or pasture. The only exception is the SSP4-3.4 scenario, with a pronounced expansion of secondary non-forested land at the expense of the primary non-forested land. Here, "secondary" refers to land previously disturbed by human activities and recovering, while "primary" refers to land previously undisturbed by human activities (Hurtt et al. 2011). In addition to this expansion, the individual scenarios vary mainly in the fractions of the land covered by the different types of crops or pasture. The fraction of the C3 annual crops, for instance, is relatively large for the SSP2-4.5 and relatively small for the SSP3-7.0 scenario.

The SSP1-2.6 scenario is the only SSP marker scenario in accordance with the goals of the PA. Therefore, we consider this scenario as a reference for the further analysis of the characteristics of the land types in the SSP scenarios. Figure 8.5 shows maps of nine of the 12 different land types (the urban land is not included and the forested primary land and C4 annual crops do not occur) averaged over the period 2041-2050. This decade is chosen, as it coincides with the critical point in time when the Swedish national climate policy aims at not having any net emissions of GHGs (see Chapter 2.2). According to this, the secondary forest covers the northern, central and south-western parts of Sweden in the SSP1-2.6 scenario. In particular, non-forested primary land and non-forested secondary land prevail in the south-eastern part of the country. Cropland (mostly C3 annual crops) is primarily located in southern Sweden and along the coast of the Baltic Sea and pasture mainly in a latitudinal band between about 58 and 60 °N, ranging over the entire country.

The panel for the SSP1-2.6 scenario in Figure 8.4 reveals only small variations in the area fractions covered by a particular type of lands use, but some changes over time do occur. At the end of the 21st century (2091-2100), both C3 and C4 perennial crops are cultivated in Sweden (Fig. 8.6). This happens mainly at the expense of pasture (both managed pasture and rangeland). Much of the non-forest primary land is transformed into non-forested secondary land. The area with the C3 annual crops is extended northward (at the expense of the secondary forest), while the area fractions covered with C3 annual crops are either decreased or increased in various areas in the southern part of the country. Furthermore, secondary forest is reduced, especially in the south-western part of Sweden, where it is typically replaced by C3 annual crops.

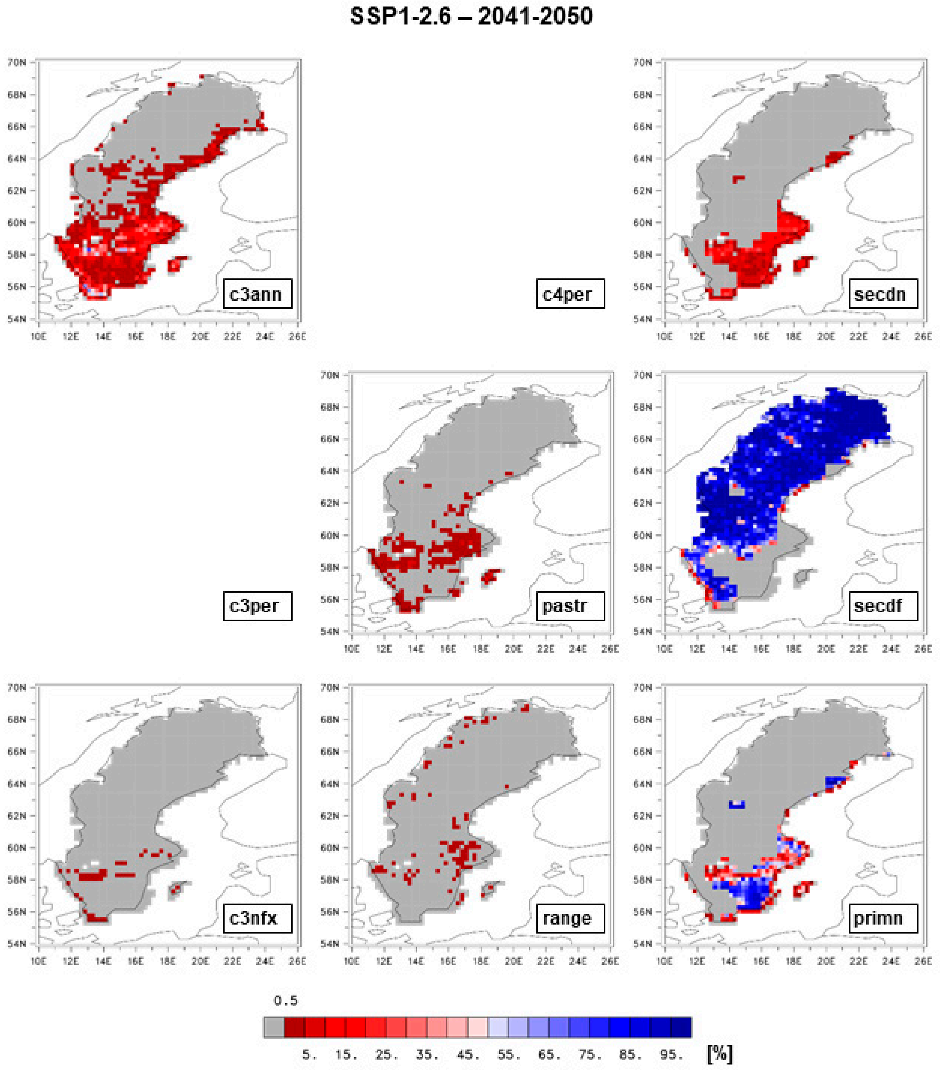


Fig. 8.5: Long-term means (2041-2050) of the fractions of grid points covered with nine different land-use states, i.e. C3 annual, perennial and nitrogen-fixing crops, C4 perennial crops, managed pasture, rangeland, potentially non-forested and forested secondary land as well as non-forested primary land (see Table 8.2 for acronyms), for the SSP1-2.6 scenario from the LUH2 data set. The maps for the perennial crop types are omitted, since the values are zero for all of Sweden for this scenario

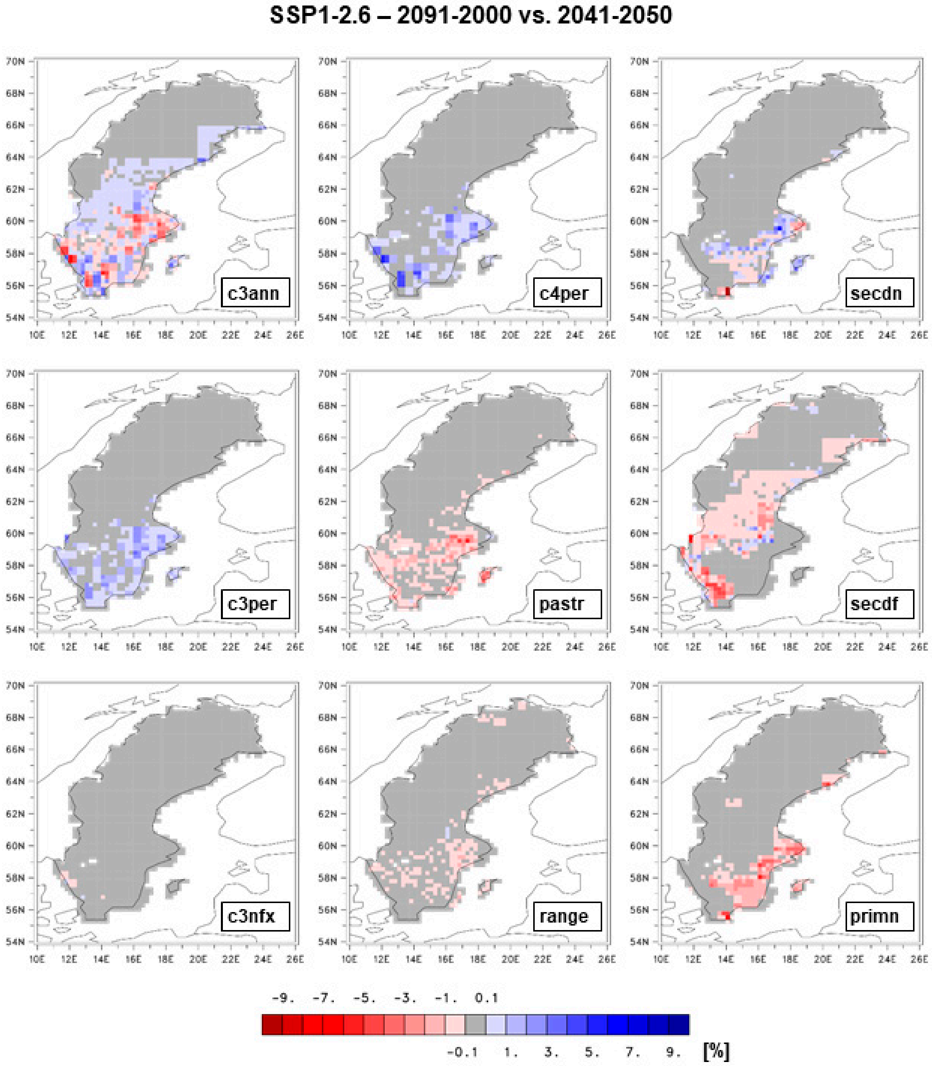


Fig. 8.6: Differences between the long-term means for 2091-2100 and 2041-2050 of the fractions of grid points covered with nine different land-use states for the SSP1-2.6 scenario from the LUH2 data set

Figure 8.4 also indicates some small variations between the different SSP scenarios, which are illustrated in Figures 8.7 to 8.11. Here, the differences between the five SSP scenarios and the SSP1-2.6 scenario for the middle of the 21st century (2041-2050) are presented. For cropland, the strongest variations are found for the C3 annual crops, with larger area fractions in southern Sweden in the SSP2-4.5 (Fig. 8.7), SSP4-3.4 (Fig 8.9) and SSP4-6.0 scenario (Fig. 8.10). For the SSP3-7.0 scenario, on the other hand, the area fraction of the C3 annual crops is smaller (Fig. 8.8). SSP4-3.4 and SSP4-6.0 are the only scenarios with C4 perennial crops at the middle of the 21st century. For pasture, the two scenarios with the strongest radiative forcing, i.e. SSP3-7.0 and SSP5-8.5 (Fig. 8.11), are characterized by larger area fractions than for the SSP1-2.6 scenario, both for managed pasture and rangeland. In the other scenarios the area fractions for the two kinds of pasture are either lower (SSP4-3.4) or larger in some areas and smaller in others. In all scenarios, the fractions of the primary natural land are smaller than for the SSP1-2.6 scenario. The area fractions of the secondary natural land, on the other hand, are only smaller for the SSP2-4.5 and the SSP5-8.5 scenario and larger for the SSP3-7.0 scenario. This leaves SSP2-4.5 as the scenario with the lowest area fractions of the two kinds of non-forested land at the middle of the 21st century. In SSP2-4.5, the area fractions of secondary forest are also smaller almost everywhere, while for the SSP5-8.5, SSP4-3.4 and SSP4-6.0 scenario they are only smaller in the south-western part of Sweden and in a slightly tilted latitudinal band between about 58 and 62 °N. In SSP4-3.4 and SSP4-6.0, however, the area fractions of secondary forest are larger in some regions of the central and northern parts of Sweden.

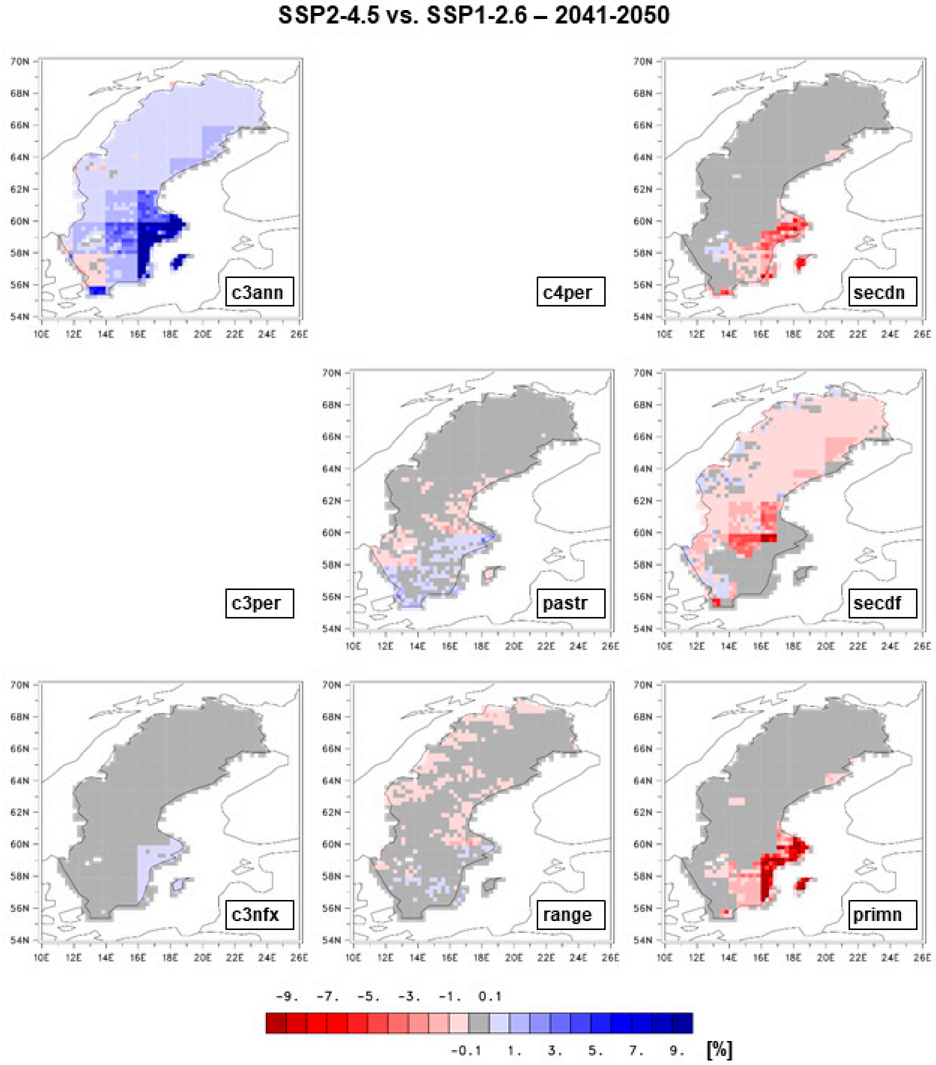
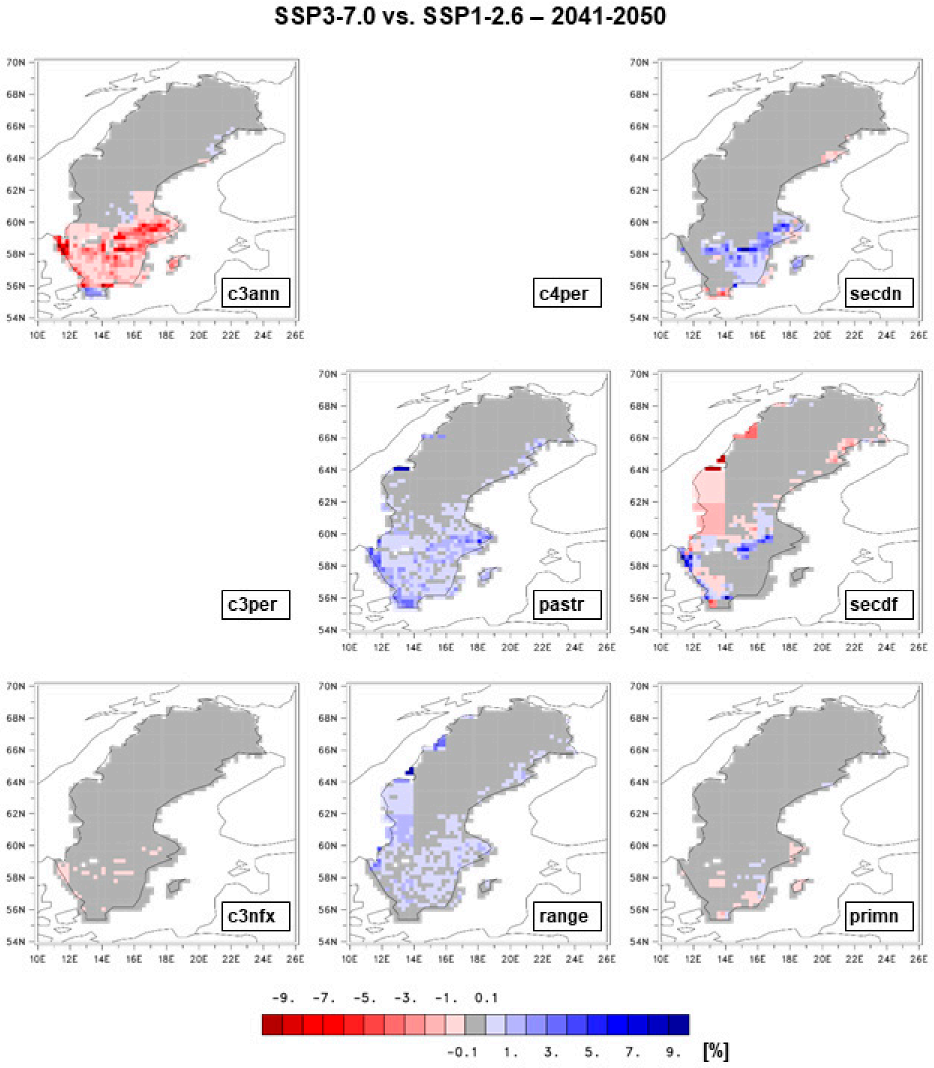


Fig. 8.7: Differences of the long-term means (2041-2050) of the fractions of grid points covered with nine different land-use states between the SSP2-4.5 and the SSP1-2.6 scenario from the LUH2 data set. The maps for the perennial crop types are omitted, since the values are zero for all of Sweden for both scenarios



SSP3-7.0 vs. SSP1-2.6 – 2041-2050

Fig. 8.8: As Fig. 8.7 but for the SSP3-7.0 scenario

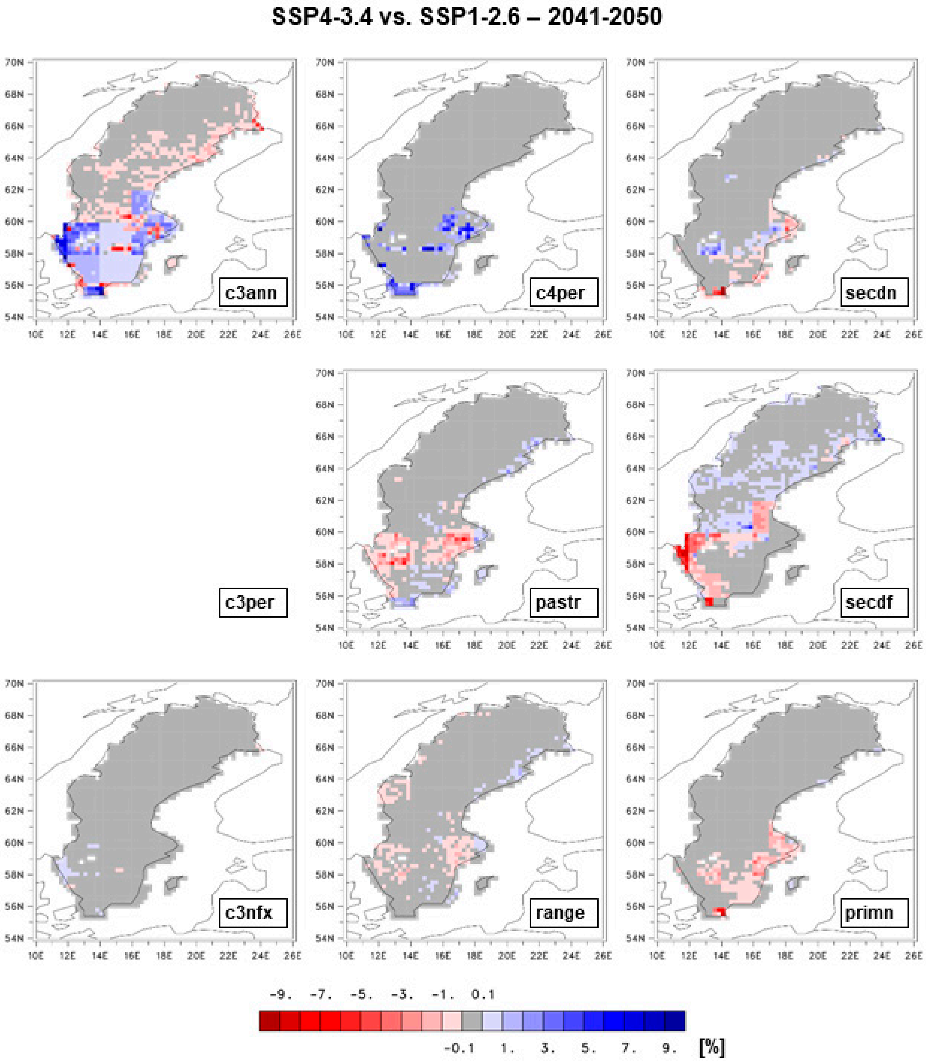


Fig. 8.9: As Fig. 8.7 but for the SSP4-3.4 scenario. In this case, only the map for C3 perennial crops is omitted

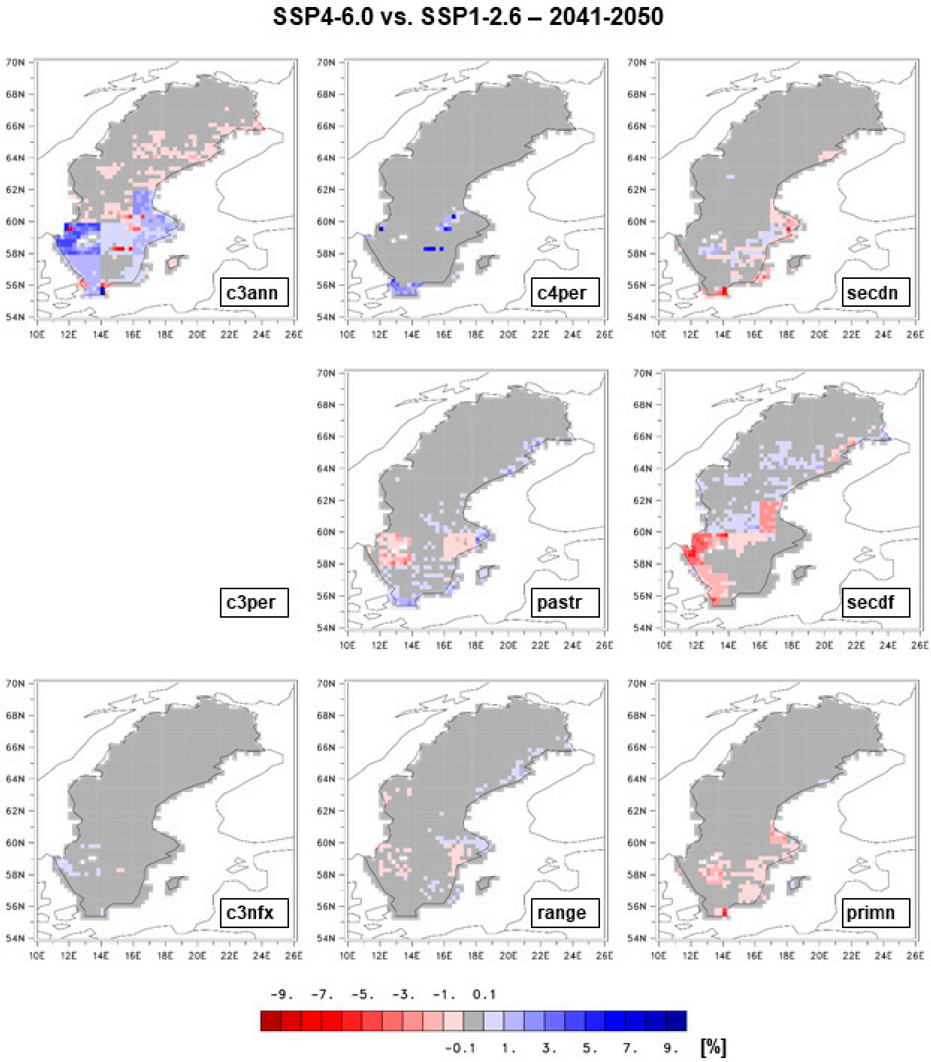


Fig. 8.10: As Fig. 8.7 but for the SSP4-6.0 scenario. In this case, only the map for C3 perennial crops is omitted

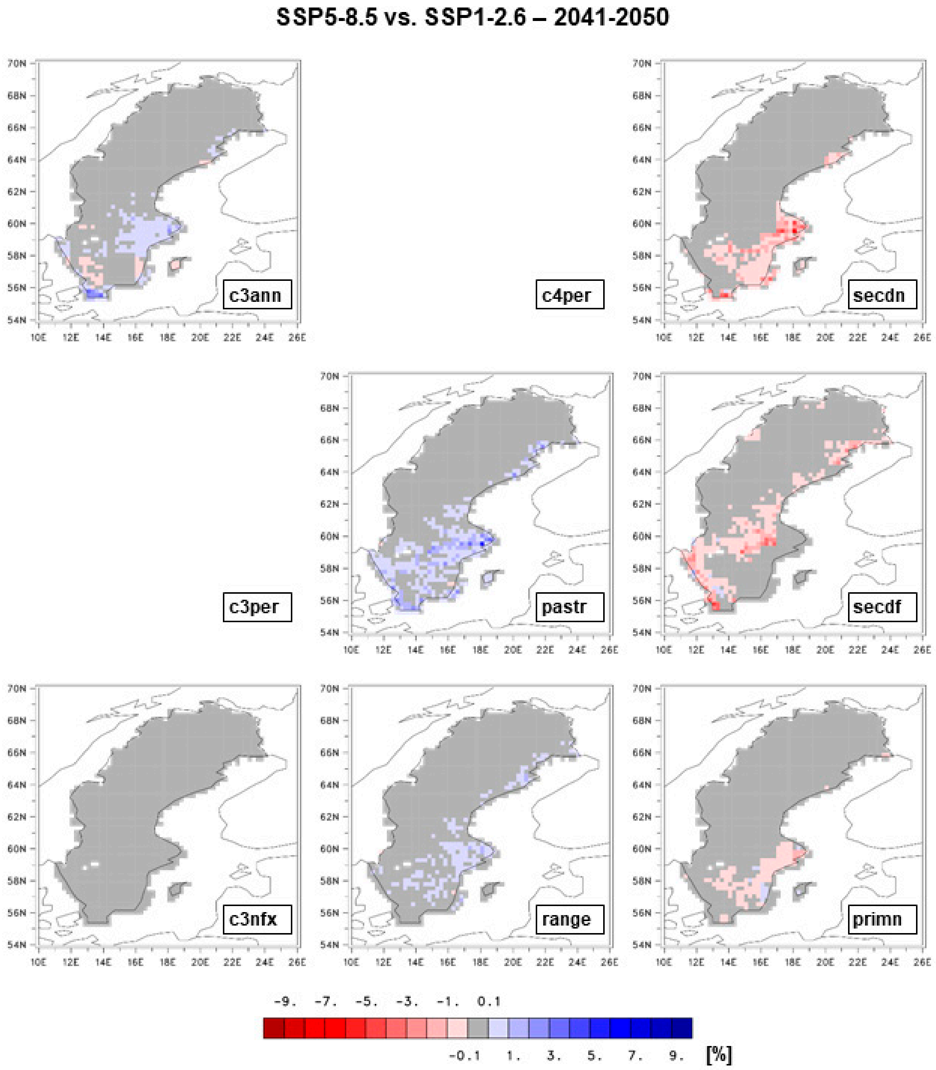


Fig. 8.11: As Fig. 8.7 but for the SSP5-8.5 scenario

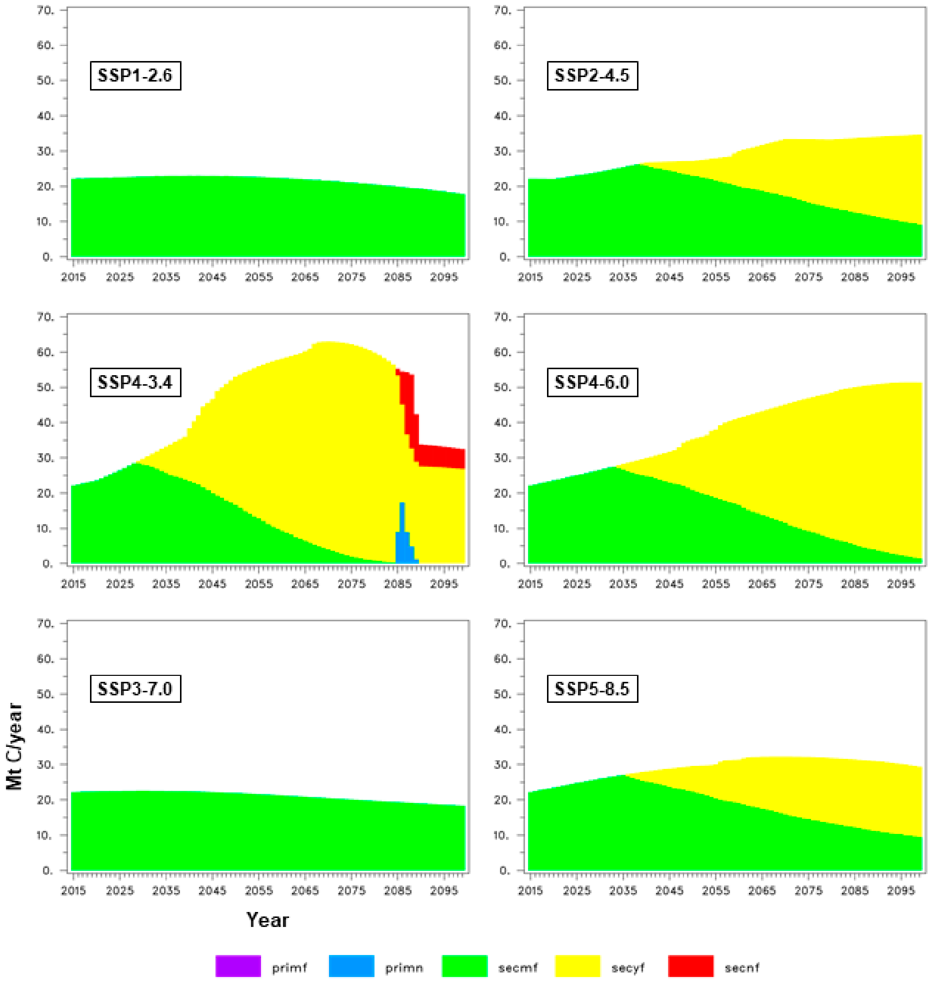


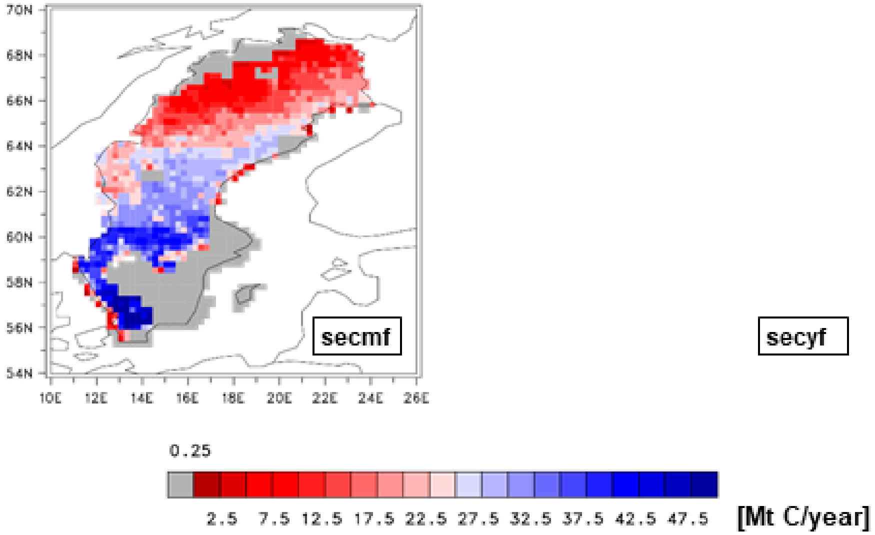
Fig. 8.12: Temporal evolution (from 2015 to 2100) of the biomass of the wood harvest for Sweden from five different land-use states, i.e. primary forest and non-forest, mature and young secondary forest as well as secondary non-forest (see Table 8.3 for acronyms) for six different SSP-scenarios from the LUH2 data set

The LUH2 data set also includes information on the biomass of the wood harvest from different types of land, i.e. primary forested (not existing in Sweden) and non-forested land, secondary mature and young forest as well as secondary non-forested land (see Table 8.3 for an overview). Figure 8.12 shows the temporal evolution of the annual biomass harvest accumulated over Sweden related to these land types for the six SSP scenarios. SSP1-2.6 and SSP3-7.0 are the only scenarios where biomass is only harvested from secondary mature forest in Sweden, while for the other scenarios more and more wood is harvested from secondary young forest in the course of the century. At the same time, the wood harvest from mature forest decreases more and more. The biomass harvested from the secondary young forest is particular large for the SSP4-3.4 and the SSP4-6.0 scenario. Overall, the SSP4-3.4 scenario is characterized by a biomass harvest of more than 60 Mt C/year in the 2060's and 2070's from secondary forest, while the SSP1-2.6 and SSP3-7.0 scenario only give 20 Mt C/year, which is slightly less than the estimated biomass from wood harvest in 2015. Moreover, the SSP4-3.4 scenario differs from the other scenarios in two respects. Firstly, this scenario reaches a distinct top between 2055 and 2085 and shows a considerable decrease after 2085, reducing the biomass harvest by about 50% at the end of the 21st century. Furthermore, in this scenario biomass is also harvested from secondary and primary non-forested land. As for the secondary land, the harvest continues until the end of the century, while for the primary land, the harvest is confined to several years until all the non-forested primary land is transformed into secondary land (see Fig. 8.4).

In the SSP1-2.6 scenario, the amount of biomass harvested from secondary mature forest varies considerably by region at the middle of the 21st century (Fig. 8.13). The wood harvest is particularly intense in the south-western and central parts of Sweden and less intense in the northern part. At the end of the 21st century, the wood harvest is reduced in all of Sweden except for the very northern part along the border with Norway. In all other scenarios except for RCP3-7.0, this region is characterized by a rather intense wood harvest already at the middle of the century (Figs. 8.14, 8.15). In both the SSP3-7.0 and the SSP4-3.4 scenario, the amount of biomass is smaller than for SSP1-2.6 over the rest of Sweden, while in SSP2-4.5, SSP4-6.0 and SSP5-8.5 the wood harvest is slightly more intense in many regions in the central and northern parts of the country. As for the biomass harvested from young secondary forest, the intensity varies between the scenarios at the middle of the 21st century (as illustrated in Fig. 8.12), with the highest amount of biomass in SSP4-3.4 and the lowest in SSP2-4.5. In all four scenarios, the wood harvest is more intense in the south-western and central parts of Sweden and less intense in the northern part.

The LUH2 data set also contains information on the fractions of the areas for the five different crop types that are grown as biofuels. In all SSP scenarios, only C3 nitrogen-fixing crops are grown as biofuel in Sweden at a constant (both in time and for the different scenarios) rate of about 20% of the respective area. As only very small fractions of Sweden are used to grow this particular crop type (see Fig. 8.5), we do not present any corresponding curves or maps here.

SSP1-2.6 – 2040-2049



SSP1-2.6 – 2090-2099 vs. 2040-2049

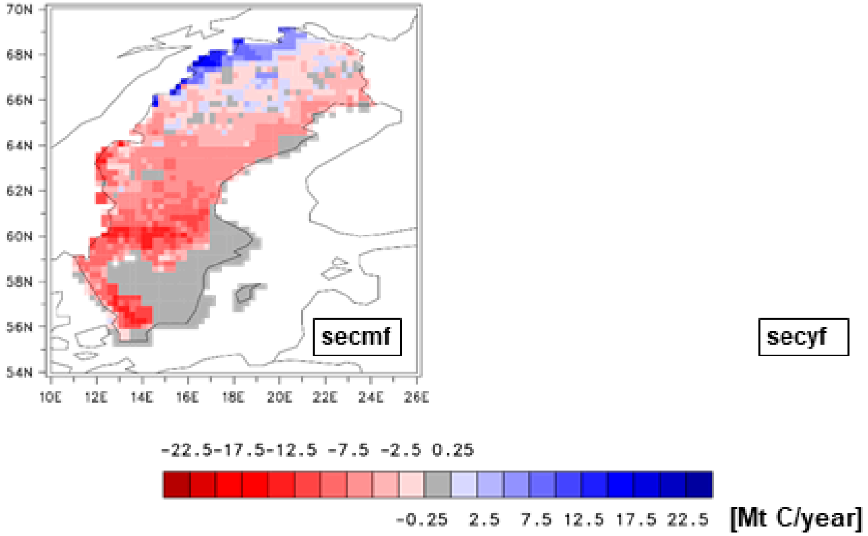


Fig. 8.13: Long-term means (2040-2049; upper row) of the biomass of the wood harvest from two land-use states, mature and young secondary forest (see Table 8.3 for acronyms), for the SSP1-2.6 scenario from the LUH2 data set, and the differences between the long-term means for 2090-2099 and 2040-2049 (lower row). The maps for the young forest are omitted, since the values are zero for all of Sweden for this scenario for both periods

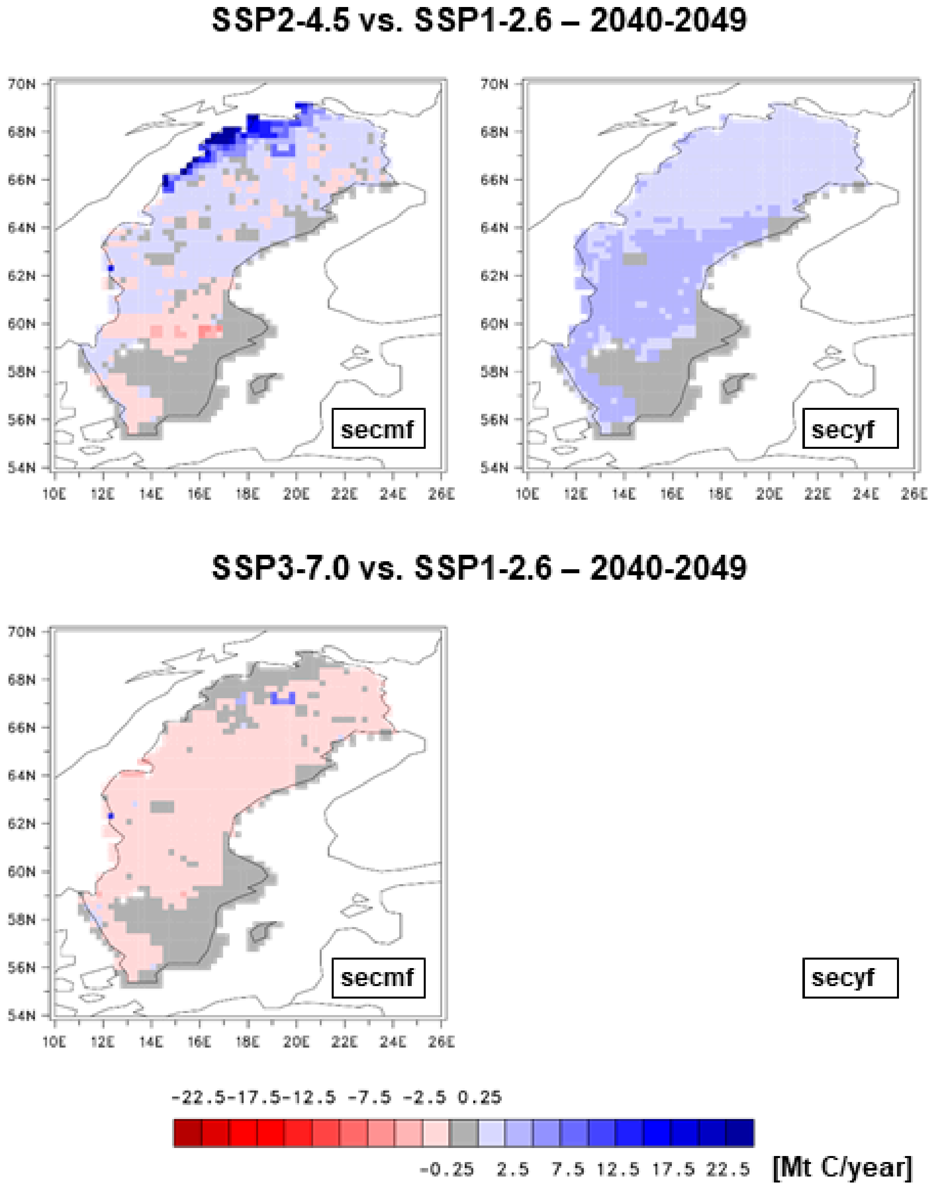


Fig. 8.14: Differences of the long-term means (2040-2049) of the biomass of the wood harvest from two land-use states between the SSP2-4.5 and the SSP1-2.6 scenario (upper row) and between the SSP3-7.0 and the SSP1-2.6 scenarios (lower row) from the LUH2 data set. The maps for the young forest are omitted for the second case, since the values are zero for all of Sweden for both scenarios

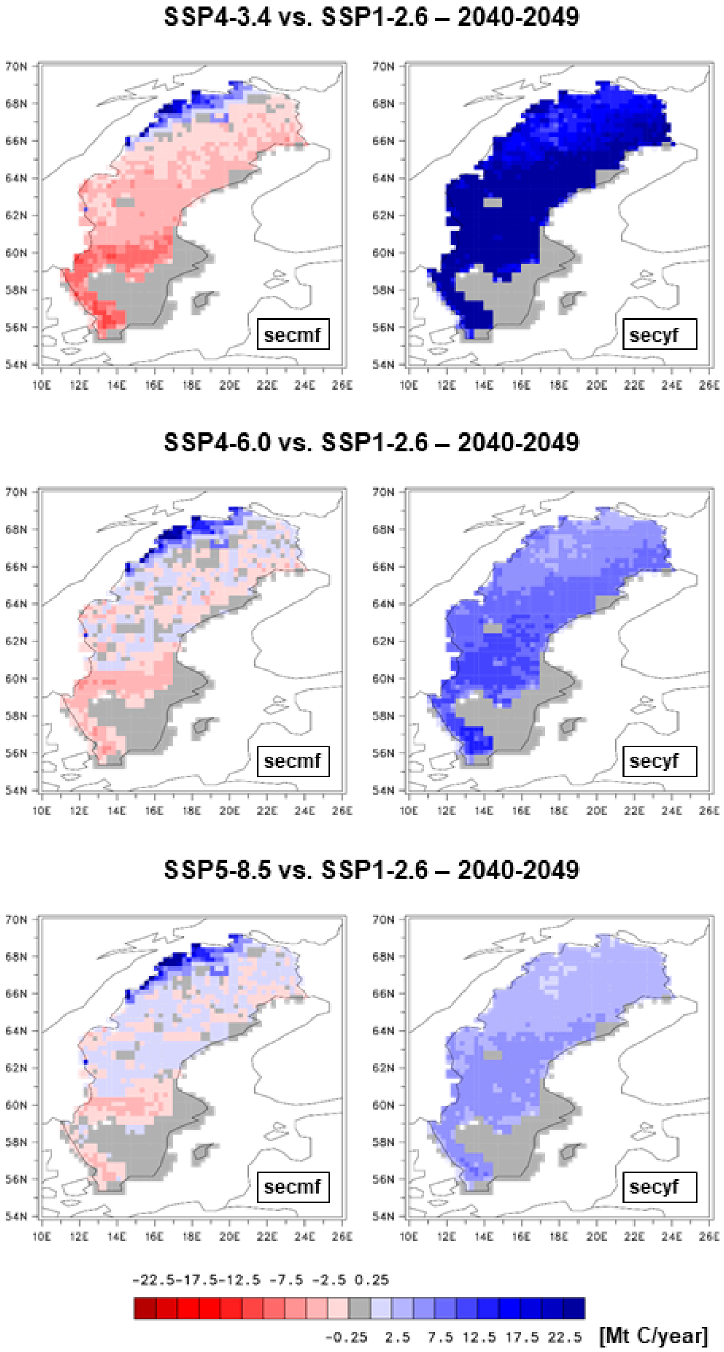


Fig. 8.15: As Fig. 8.14 but for the SSP4-3.4 (upper row), the SSP4-6.0 (middle row) and the SSP5-8.5 scenario (lower row)

8.3 Uncertainties of land-cover projections

In addition to the uncertainties inherent to the method used to obtain the land-use and land-cover scenarios (see Chapter 2.7), different IAMs give a rather wide range of possible land cover changes for a specific SSP scenario (Figs. 8.2, 8.3). Alexander et al. (2017) analysed the variations between land-cover projections in further detail and quantified the uncertainties in global and European land-cover projections over a range of model types and scenarios. Figure 8.16 shows the change of the three main land-cover types, i.e. cropland, pasture and forest, for the 27 member states of the EU (EU27) for various models and scenarios. Considering the absolute areas revealed not only strong variability between the changes simulated by different models but also very large differences between the initial conditions (i.e. the values at the start of the simulations) of these models. This was particularly the case for pasture and to a lesser extent for cropland and forest. For pasture the initial conditions are about 25 to 110 mio ha (with an observational estimate of slightly less than 75 mio ha), for cropland about 85 to 145 mio ha (approximately 135 mio ha observed) and for forest about 120 to 190 mio ha (about 145 mio ha observed). These differences in the initial conditions persisted to a large extent over the course of time. The main reasons for these discrepancies are the uncertainty in the magnitude of the current areas and differences in the definition of land-cover types. Hurtt et al. (2011) corrected for the different initial conditions when preparing the land-use scenarios based on the SSP marker scenarios through harmonization, i.e. by smoothly connecting the spatially gridded historical reconstructions of land-use changes with the future projections originating from the various IAMs. An alternative way to correct for these differences is by scaling to a common starting point. Despite the scaling, three of the models give many of the more extreme area changes for the EU27 member states. The simulations with these and other extreme models do typically not extend past 2050.

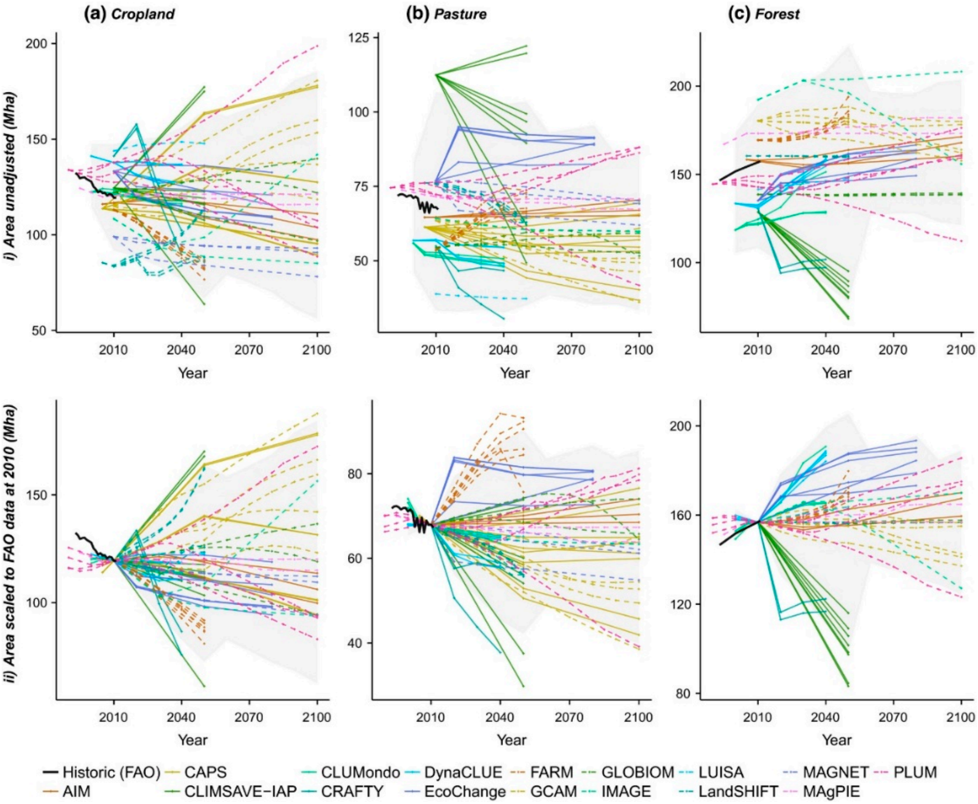


Fig. 8.16: Modelled land cover areas for cropland (a), pasture (b) and forest (c) for the EU27 member states from 16 models and a total of 64 scenarios. A historical dataset from 1993 to 2011 is shown as solid black lines. The absolute areas are shown in i) and the areas scaled to match the historical data in 2010 are shown in ii). The scaled data were determined by rebasing all results to FAO areas at 2010 and then applying the same scaling for all time points of that type, model and scenario. From Alexander et al. (2017)

In addition, it is not clear to which extent the land-use and land-cover data from LUH2 realistically represent conditions in Sweden. This is the case for the reconstruction that is used to describe historical land use and land cover before 2015, and, possibly, also for the categorization in the different lands-use categories itself. But this also applies to the future scenarios of LULCC, with the underlying IAMs often incorporating processes operating at regional or global scales. Some of these processes will also have an impact on Swedish policies, but the implementation of these policies is a national task and decisions on specific adaption and mitigation measures are taken at a national level as well.

9. Modelling the biophysical and biogeochemical effects of land-use and land-cover change on climate

9.1 Introduction

Numerical models play an important role for developing future scenarios for GHG emissions or land-use changes and future climate scenarios in response to these forcing scenarios. These models have different levels of complexity, depending on their specific purposes and their structure. These include the widely used integrated assessment models, physical climate models (GCMs simulating the states of the atmosphere, the ocean and the sea-ice) and earth system models.

Van Vuuren et al (2012) explained the basic principles of IAMs and ESMs and evaluated the advantages and disadvantages of different types of collaboration between the IAM and ESM community, ranging from offline models over improved (i.e. more comprehensive) IAMs and ESMs to fully coupling IAMs and ESMs (IA-ESMs). Figure 9.1 gives a schematic overview on IAMs and ESMs and illustrates the linkages between the two kinds of models. IAMs include only a simplified version of the natural earth systems but an advanced representation of the human systems. ESMs, on the other hand, incorporate detailed representations of various processes governing natural earth systems but lack the human dimensions, other than as forcings. Linkages between IAMs and ESMs include the provision of GHG emission scenarios and land-use changes associated with potential socioeconomic developments by the IAMs and linkages between ESMs and IAMs involve climate variables. Some of the linkages between the two types of models can lead to feedbacks that dampen or strengthen the original signal.

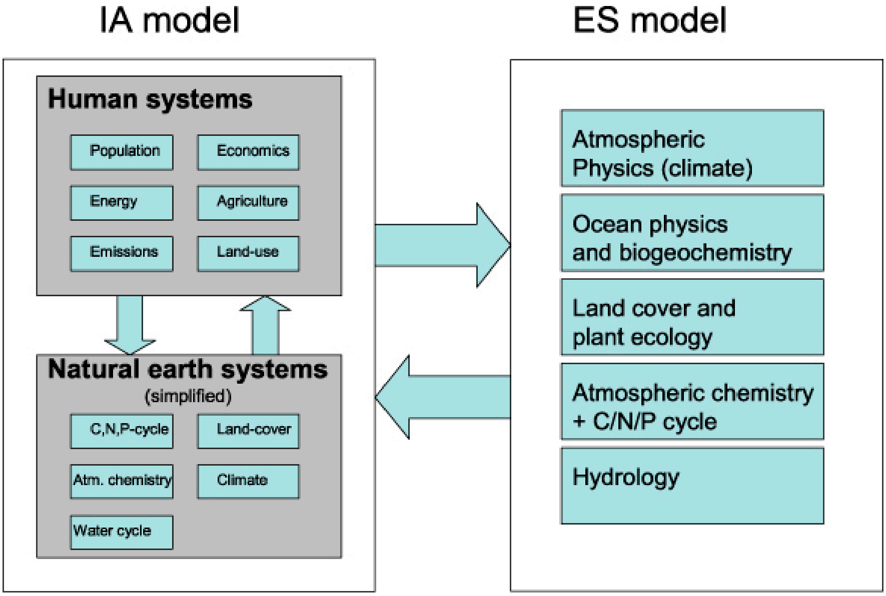


Fig. 9.1: Overview of some main components of Integrated Assessment Models (IAMs) and Earth System Models (ESMs). The two vertical arrow illustrate the linkage between the human system and natural earth system components that already exists in IAMs. From Van Vuuren et al. (2012)

Currently, the two kinds of models are typically run separately and information is exchanged in one direction from an ESM to an IAM or vice versa. Advantages of this approach are the transparent information exchange, flexibility and the possibility of separate research strategies in the respective communities. An important disadvantage is the fact that feedbacks are not represented, possibly generating inconsistencies between the different kinds of models. Before fully coupling IAMs and ESMs and, thus, incorporating various feedbacks, each kind of model needs to be improved to actually represent the responses to a specific forcing from the other model. Most IAMs, for instance, do not include the impact of climate change on the energy demand for heating and cooling or the impact of extreme drought on crop yield. This is mainly because the knowledge on such impacts is considered too uncertain to be translated into equations in the IAM. Improving IAMs has the advantages of a good representation of the range of uncertainty, the fact that the complexity of the model is tailored to a specific question and the detail in the treatment of socioeconomic processes. The main disadvantage is the lack of detail in the treatment of biophysical processes in IAMs. ESMs, on the other hand, lack a detailed treatment of socioeconomic processes and, due to a restricted number of simulations feasible with such a complex model, representing uncertainty only to a limited extent. Fully coupled (improved) IAMs and ESMs combine the aforementioned advantages of the respective type of models. IA-ESMs, for instance, allow for assessing various kinds of feedbacks and have the highest level of consistency. However, IA-ESMs also bring about technical difficulties and have a limited representation of the range of uncertainty.

Van Vuuren et al. (2012) gives a wide range of examples on potential interactions between the human and the earth system and relates those interactions to the different kinds of model configurations mentioned before, i.e. common IAMs and ESMs run offline, improved IAMs and ESMs and fully coupled IAMs and ESMs. These examples include the impacts of climate change on energy use and on transport and shipping as well as the interactions between climate change and land use, between air pollution and crop growth and between climate policy and air pollution policies. Other examples are the impacts of droughts and the availability of water on societies, mitigation policy responses to realized or projected climate change or the avoidance of particular regional climate change and related impacts. The interaction between climate change and land use or land cover is one of the most important aspects of the interplay between the human and the earth system. On one hand, ESMs often incorporate dynamical vegetation and, on the other, human activities play an important role for land-use and land-cover changes, potentially leading to several relevant feedbacks between the two systems. Climate change, for instance, can influence decisions (all simulated within an IAM) on where to grow crops and which management approaches to apply, which in turn affect climate via GHG emissions and surface albedo, simulated in an ESM.

9.2 Standard modelling tools

Integrated assessment models

Many issues related to climate change concern both the human and the earth system and, thus, include socioeconomic as well as biogeochemical components. These are, for instance, measures to ameliorate the impacts of future climate change such as the mitigation of GHG emissions or the adaptation to the impacts of climate change. Because the interactions within and between the socioeconomic and the biogeochemical components of the earth system can be quite complex, a number of quantitative models have been developed to investigate large-scale climate changes and the effects of various types of public policies on projections of future climate change. These models have become known as models for the “integrated assessment of climate change” or IAMs. An exhaustive review on IAMs is given in Weyant (2017). All IAMs include economic and natural processes that govern GHG emissions. These emissions are used to drive a representation of the global carbon cycle and the chemical composition of the atmosphere, which is then used to determine changes in climate and sea level. The models then project, how these changes impact natural systems on earth, with some of them being managed by humans. IAMs differ enormously in their level of detail, their complexity and the interactions they consider. Some models, for instance, represent the whole earth system with a small number of fairly simple equations, while others include thousands of equations drawn from physics, chemistry, biology and economics.

There are two basic types of IAMs, the detailed process (DP) IAMs and the benefit-cost (BC) IAMs. Although both types of IAMs include projections of GHG emissions and the costs associated with various options to mitigate them, they handle the impacts of climate change differently. DP IAMs are more separated into components and aim at providing projections of climate change impacts at detailed regional and sectoral levels, with some of them using economic evaluation and others using projections of physical impacts (e.g. reductions in crop growth, land inundated by sea level rise or additional deaths from heat stress). BC IAMs, on the other hand, provide a more aggregated representation of the costs for climate change mitigation and combine impacts by sector and region into a single economic metric. DP IAMs provide more information than BC IAMs on the physical impacts and economic costs of climate change and on the benefits of mitigating GHG emissions. The additional information on both the physical and the economic impacts of climate change available from DP IAMs may be highly important to decision makers in certain regions or sectors.

Van Vuuren et al. (2011) investigated how well IAMs simulate climate change, focussing on several policy-relevant questions that follow a causal chain. These questions are: 1. What is the equilibrium temperature level for a particular stabilisation of radiative forcing? 2. What is the transient temperature response before temperature stabilisation is reached? 3. How does the radiative forcing respond to changes in CO_2 concentration? 4. How does the carbon cycle behave, including feedbacks? 5. What is the overall model behaviour under a high emission scenario? 6. What is the overall model behaviour under a stringent overshoot mitigation scenario? The authors found a significant spread in the simulation of the climate system and the carbon cycle between the IAMs considered in their study. A comparison with results from coupled atmosphere-ocean GCMs and ESMs revealed that the outcomes from IAMs were in the range of the outcomes from the complex climate models, but that the differences between IAMs and the complex climate model were large enough to matter for policy advice. As areas where IAMs would benefit from improvements the authors identified climate sensitivity, inertia in the climate response and carbon cycle feedbacks.

Only two of the five IAMs used to derive the SSP marker scenarios (see Chapter 8.1) include a dynamical vegetation model to explicitly simulate the terrestrial carbon cycle and vegetation dynamics. These are IMAGE (Van Vuuren et al. 2017) and REMIND-MAgPIE (Kriegler et al. 2017). Both IAMs include the Lund-Potsdam-Jena model for managed Land (LPJmL; Bondeau et al. 2007, Müller et al. 2016), and land-use changes are covered in IMAGE and MAgPIE. In the three other IAMs vegetation dynamics are not considered, and the terrestrial carbon cycle and land-use changes are simulated with varying levels of complexity.

Earth system models

Earth system models are global climate models with the added capability to explicitly represent biogeochemical processes that interact with the physical climate (see Fig. 1 in Bonan and Doney 2018). These interactions alter the climate response to anthropogenic forcing, i.e. GHG emissions or land-use and land-cover changes. Representing the carbon cycle, for instance, allows for feedbacks between the physical climate and the biological and chemical processes in the ocean and on land, which capture some of the emitted carbon. These feedbacks can reduce or enhance the warming induced by GHG emissions (e.g. Friedlingstein et al. 2014). When investigating the carbon feedback in 11 ESMs, the authors found that seven models simulated increased atmospheric CO_2 due to the carbon cycle feedback and, thus, an additional warming, with considerable inter-model variability. The remaining four models simulated a reduction in atmospheric CO_2. The authors attributed the great uncertainty in the sign and the magnitude of the carbon cycle feedback to uncertainties in the response of the land carbon cycle. The latter was partly due to the fact that not all the ESMs included land-use changes in the calculations of the net fluxes of CO_2 between land and atmosphere. The sulphur cycle is also important because sulphur emissions (both natural and anthropogenic) contribute to the production of sulphate aerosols. These aerosols reflect incoming solar radiation and, thus, have a direct cooling effect on climate and they alter the properties of clouds and, by this, have an overall indirect cooling effect. A detailed review on ESMs is given in Flato (2011).

One way to further develop ESMs is to improve the representation of specific processes or to include additional processes into the models. This is because many processes related to potentially important feedbacks are still not completely understand or rather crudely represented in the current generation of ESMs. These deficits contribute to the uncertainty in future climate projections. Feedbacks involving clouds, i.e. their role in radiative forcing and the connection between clouds and aerosols are a main source of uncertainty. Other important sources of uncertainty relate to plant photosynthesis and its dependence on both CO_2 and nutrient availability, decomposition of soil carbon and its dependence on soil temperature and moisture, including areas underlain with permafrost, wetlands and their emissions of CH_4 as well as wildfires and their role in the global carbon budget. Another important aspect is the inclusion of the nitrogen cycle into the ESMs in order to model the uptake of CO_2 by plants in a more realistic way. Nitrogen was found to buffer the terrestrial ecosystems' response to changing CO_2 and changes in climate (e.g. Levis et al. 2010). Only two of the ESMs contributing to CMIP5, however, included an interactive nitrogen cycle, incorporating nitrogen limitations on plant productivity (Arora et al. 2013). A current horizon in ESM development concerns the implementation of an active phosphorous (P) cycle, potentially improving the simulation of terrestrial ecosystems in the tropics and dry climates zones, where the availability of P is often considered to limit plant productivity (e.g. Reed at al. 2015). Inevitably, biases in the climate simulated by ESMs need to be further reduced, as they have been found to have a large influence on the simulation of terrestrial ecosystems and, hence, the simulation of the terrestrial carbon cycle (Ahlström et al. 2017). The authors found that climate biases could be responsible for 40% of the large uncertainties in ESM simulations of land carbon fluxes and pools.

Regional earth system models

Although the horizontal resolution of coupled atmosphere-ocean GCMs and ESMs has markedly increased through the last decade (some have a resolution below 100 km), they are still relatively coarse. Thus, they do not realistically represent orographic features or local and regional land-surface conditions, e.g. variable orography, coastlines, land-sea contrasts, water bodies such as lakes, as well as vegetation and land use. Many of these aspects are better represented (or even included as components) in regional climate models, with a typical resolution of 10-20 km for simulations covering entire continents.

Rummukainen (2016) discussed the "added value" that simulations with RCMs actually have as compared to the simulations with the global climate models used to drive the RCM, given that some aspects are captured more realistically. In regions that are affected by orographic features or local and regional land-surface conditions, RCMs provide added value for simulations under present-day climate conditions. This is particularly the case for short-duration extreme events and various mesoscale meteorological phenomena, e.g. cyclones, polar lows or cutoff lows. For certain phenomena, i.e. extreme daily precipitation events in mountainous regions, the added value originates not only from the finer resolution but from specific physical mechanisms activated by the fine-scale topography and resolved land-water contrast (e.g. Thiery et al. 2015) or explicitly simulated at fine resolution such as convection (e.g. Prein et al. 2015). Also for simulations under future climate conditions, RCMs provide added value and not merely additional details. This is the case, when the differences in the future climate projections between the RCM and the driving global climate model can be related to specific physical processes.

In many applications, RCMs only comprise a regional model of the atmosphere where, in addition to the lateral boundary conditions, the surface conditions (i.e. SST and sea ice) are prescribed as well. Depending on the character of the specific applications, RCMs have been extended to include other components representing the physical climate system, further enhancing the added value of RCM simulations. These are, for instance, RCMs interactively coupled with a lake model (e.g. Samuelsson et al. 2010, Thiery et al. 2015), coupled atmosphere-ocean RCMs for particular ocean basins (e.g. Wang et al. 2015a) or coupled atmosphere-ocean RCMs especially designed to include the interactions with the cryosphere (e.g. Koenigk et al. 2011). RCMs have also been expanded to incorporate interactions with chemistry or with aerosols, the latter having various direct and indirect effects on climate (see Chapter 9.2). Examples are the inclusion of mineral aerosols (e.g. Ji et al. 2016) or different kinds of anthropogenic aerosols (e.g. Wang et al. 2015b).

Finally, RESMs extending RCMs to include the biosphere, interactively coupling model components representing vegetation dynamics and biogeochemistry, have been developed. RCA-GUESS, jointly developed by researchers at LU and SMHI, was the first published RESM (Smith et al. 2011). Currently, two other RESMs are available, CRCM-CTEM and RCM-CLM-CN-DV (see Table 9.1). Details on RCA-GUESS and examples of application of this RESM have already been given in Chapter 4.3. In CRCM-CTEM (Garnaud et al. 2015), the Canadian Regional Climate Model (CRCM) is interactively coupled with the Canadian Terrestrial Ecosystem Model (CTEM). CTEM is a process-based ecosystem model designed to simulate the terrestrial carbon cycle (e.g. Li and Arora 2012). It is able to grow vegetation from bare ground and to simulate several structural attributes of vegetation, i.e. LAI, vegetation height, root distribution and canopy mass. It includes processes such as photosynthesis, autotrophic and heterotrophic respiration, phenology, turnover, allocation, fire and land-use change. CTEM simulates two dead carbon pools (litter and soil carbon) and three living vegetation pools (stems, leaves and roots). The terrestrial ecosystem processes are modelled for nine different PFTs, i.e. evergreen and deciduous needleleaved trees, broadleaved evergreen, cold and drought deciduous trees, C3 and C4 crops as well as grasses. CRCM-CTEM has been applied in climate simulations covering North America. Garnaud et al. (2015) studied the effect of incorporating dynamical vegetation in the climate model under present-day climate conditions. The authors found that the inclusion of the interactive phenology in the climate model intensified the interactions between the biosphere and the atmosphere and introduced long-term memory to the climate. Furthermore, the simulation of interannual climate variably was improved, particularly in relation to anomalously wet or dry years. Garnaud and Sushama (2015) investigated the role of the interactive vegetation phenology for future climate projections. The results showed that the interactive phenology led to a longer growing season and, thus, to a higher annual vegetation productivity and biomass under future climate conditions. In spring, the interactive vegetation phenology enhanced the warming over much of North America by altering the surface albedo. In summer, it enhanced the future warming over the northern part of the continent but attenuated the warming over the southern part due to hydrological feedbacks.

Table 9.1: Regional earth system models including a comprehensive representation of vegetation dynamics and biogeochemistry. The list of applications may not be complete

Model	Atmospheric circulation model	Terrestrial ecosystem model	Reference paper	Other papers (applications)
RCA-GUESS	Rossby Centre Regional Atmospheric Model (RCA)	Lund-Potsdam-Jena General Ecosystem Simulator (LPJ-GUESS)	Smith et al. (2011)	Wramneby et al. (2010) Lindeskog et al. (2013) Zhang et al. (2013, 2014b, 2018) Wu et al. (2015, 2016)
CNRM-CTEM	Canadian Regional Climate Model (CRCM)	Canadian Terrestrial Ecosystem Model (CTEM)	Garnaud et al. (2015)	Garnaud and Sushama (2015)
RCM-CLM-CN-DV	Regional Climate Model (RegCM)	Community Climate Model (CLM) including Carbon-Nitrogen Dynamics and Vegetation Dynamics (CLM-CN-DV)	Wang et al. (2016)	Yu et al. (2016) Shi et al. (2018)

Wang et al. (2016) interactively coupled the Regional Climate Model (RegCM) with an extended version of the Community Land Model (CLM; e.g. Oleson et al. 2008), also including a component to represent the terrestrial carbon and nitrogen cycles (CN) and a component to represent vegetation dynamics (DV). Wang et al. (2016) assessed the performance of the RESM in tropical Africa, using three different configurations with varying levels of complexity: RCM-CLM with prescribed LAI and fractional coverage of different PFTs, RCM-CLM-CN with prescribed PFTs but prognostic plant phenology and RCM-CLM-CN-DV in which both the plant phenology and the PFT coverage are simulated. The results indicated that all model configurations performed well in reproducing the physical climate and the surface radiative budget in tropical Africa. The simulated PFT coverage, however, is clearly too low over the arid and semi-arid regions due to an underestimation of the LAI in the RCM-CLM-CN configuration, while in the wet regions LAI is overestimated. In the RCM-CLM-CN-DV configuration, the simulated vegetation coverages in the arid and semi-arid regions are even lower and the exposure of bare soil is higher. Thus, the inclusion of the dynamical vegetation in the model exacerbates the underestimation of the PFT coverage in the arid and semi-arid regions of tropical Africa. Yu et al. (2016) applied the RESM to investigate the role of vegetation feedbacks for the simulation of future climate change in West Africa. The results showed a significant increase of the vegetation density over the southern part of the Sahel and a conversion from grass to woody plants around 7-10° N under future climate conditions. During summer the feedbacks associated with the projected change in vegetation led to increased precipitation, amplifying the projected increase in precipitation in some regions and alleviating the projected decrease in others. Furthermore, the vegetation feedbacks slightly enhanced the projected warming over much of West Africa during summer but had a significant cooling effect in the regions with increased vegetation density during winter. Overall, the authors identified a strong effect of vegetation feedback in the semiarid areas of West Africa and a weak effect in the wet tropics. Recently, Shi et al. (2018) applied the RESM over China, using the same three configurations of the RESM as Wang at al. (2016). Consistent with Wang et al. (2016), the authors found that all model configurations simulated various aspects of present-day climate over China well. The more complex configurations, RCM-CLM-CN and RCM-CLM-CN-DV, both performed better in simulating the interannual variability of temperature and the geographical distribution of precipitation but produced large biases in the temperature field. In particular, RCM-CLM-CN overestimated LAI, amplifying the cold temperature biases and alleviating the dry biases already present in RCM-CLM. During summer, RCM-CLM-CN-DV overestimated LAI in south and east China, strengthening the cold temperature bias in these regions through evaporative cooling.

9.3 Ongoing model developments

Decision-based land-use models

Despite the importance of anthropogenic LULCC for regional and global climate change and the effects of climate change on the functioning of terrestrial ecosystems and changes in land use and land cover, LULCC are poorly represented in ESMs. In their review, Rounsevell et al. (2014) explored the knowledge about LULCC modelling and the interactions with the climate system and how these processes are represented in models, identified research gaps and proposed ways forward to improve the representation of LULCC in future ESMs. The review focused on two fundamental research questions, i.e. how the land system can be better represented in ESMs and how models of the global land system can be improved by better representing human behaviour in decision-making processes. The authors concluded that LULCC models need to better conceptualize the alternatives for upscaling from the local to the global scale, involving the better representation of human agency. The latter requires, for instance, including the processes of learning, adaptation and agent evolution in the LULCC models. It also demands formalizing the role and emergence of governance structures, institutional arrangements and policy as endogenous processes as well as better theorizing about the role of teleconnections and connectivity across global networks. The review also underlined the important role of observational data for global-scale assessments and the need to coordinate synthesizing and assimilating the available data.

Engström et al. (2017) presented a novel approach for global-scale integrated assessment modelling that incorporates human decisions on the production of energy, i.e. fossil vs. clean energy, and on the usage of cropland for food production and bioenergy. The authors investigated the impacts of climate mitigation strategies (based on the different SSP scenarios) in the energy sector on global land use and the carbon balance.

This novel IAM framework incorporates different model components, i.e. a climate-economy model, a land-use model and a terrestrial ecosystem model (Fig. 9.2; see Engström et al. (2017) for further details on the individual models). The climate-economy model predicts the joint evolution of the global climate and global economy (Golosov et al. 2014). It is a macro model with micro-foundations to represent the economy and is suitable for studying the effects of different carbon taxes on the economy, using taxes as input for the maximisation of profit of companies providing energy. The profit-maximising companies take decisions on the production of energy, regulating the supply and demand under the consideration of energy prices and taxes. The use of three types of energy, i.e. oil, coal and clean energy, is determined as a market outcome with the goal that the energy supply fulfils the demand at any time. The fact that the model simulates markets explicitly makes it well suited for investigating the effects of policies, i.e. carbon taxes, on the market outcome. The land-use model PLUM simulates changes in the cropland coverage based on the changes in cereal, meat and milk consumption and changes in cereal yield in 168 countries (Engström et al. 2016). The calculations of the food demand depend on the population and the economic development in these countries. The changes in the expected cereal production are simulated via a global rule-based trading mechanism. The expected cereal production together with the cereal yield is used to simulate changes in the land area used for cereals. The output of clean energy from the climate-economy model gives bioenergy scenarios, which are translated into explicit demand of cropland for bioenergy. As the terrestrial ecosystem model, in the IAM the managed-land version of LPJ-GUESS (Lindeskog et al. 2013; see Chapter 4.3) is used for two purposes: first, to simulate the yields for wheat, maize, millet and rice, which are used as input for PLUM, for the range of scenarios considered, and, second, to simulate the combined effects of the biophysical drivers and the land-use changes on the terrestrial carbon balance. For the latter, the changes in cropland coverage at country-level are downscaled to a global grid with a horizontal resolution of 0.5°.

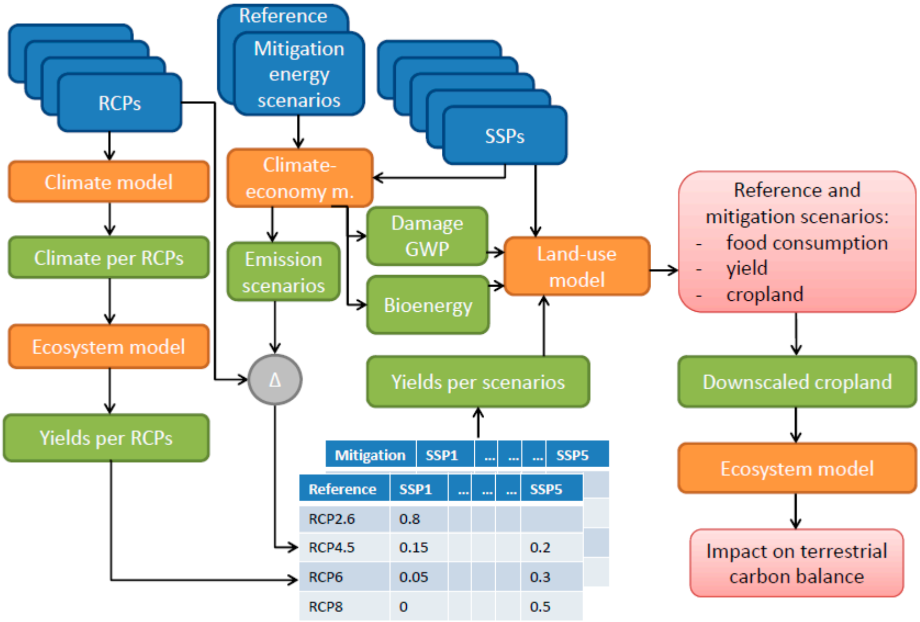


Fig. 9.2: Overview of the integrated assessment modelling framework showing input data sets in blue, component models in orange and information flows/intermediate results in green. Final results are displayed in red. The representative concentration pathways (RCPs) are input to the climate model and the shared socio-economic pathways (SSPs) are input to the climate-economy model and the land-use model. Damage to gross world product (GWP) is input to the land-use model. Δ signifies the distances between emissions predicted by the climate-economy model and implied by RCPs, used as inverse weights to create yield time series as input to the land-use model. From Engström et al. (2017)

Applying this IAM framework, Engström et al. (2017) found that when taking the emissions related to land-use changes into account the introduction of a global carbon tax on the fossil fuel sector can be an effective mitigation strategy only for scenarios with low population development and strong sustainability criteria, such as the SSP1 scenario. For scenarios with a high population growth and low technological development (i.e. the SSP5 scenario), on the other hand, the high demand of cropland for food production causes the terrestrial biosphere to turn from a sink to a source of carbon at the end of the 21st century. The results also showed that the indirect impacts of the climate mitigation strategies in the different SSP scenarios on global cropland were small compared to the impacts of variations in bioenergy productions and other sources of uncertainty, i.e. model structure and choice of parameters.

Alexander et al. (2018) applied a new model framework combing the land-managed version of LPJ-GUESS with the PLUMv2 land-use and food system model, which is a new and reconceptualised version of the PLUM land-use model from Engström et al.

(2016). PLUMv2 includes three main components, the demand for agricultural commodities at a country level for six groups (i.e. cereals, oil crops, pulses, starchy roots, ruminant products and monogastric products) for food and bioenergy production, international trade of these commodities at a global scale and the land-use combined with imports and exports at country level. The land-use information is downscaled to a global grid with a horizontal resolution of 0.5°, thus providing fine scale information on land use and land cover as well as on crop intensities, the application of fertilizers and the magnitude of irrigation to LPJ-GUESS. As part of their study, the authors applied the model framework to explore the adaptation of the land-use system to a range of future scenarios at the end of the 21st century. The results suggested that increased climate forcing results in reduced inputs of, for instance, fertilisers, pesticides or water for food production, due to the fertilisation and the enhanced water use efficiency at the elevated levels of atmospheric CO_2. At the same time, however, substantial shifts in the global and local patterns of food production are required. The results also indicated that adaptation of the global agricultural and food system can substantially contribute to abating the negative impacts of climate change and to gaining benefits from the positive effects.

These recent developments combine a terrestrial ecosystem model with advanced decision-based land-use and food system models that are suited to provide information on land-use changes at local scales. The terrestrial ecosystem model, in turn, simulates the impacts of these land-use changes on the terrestrial ecosystems, e.g. on the terrestrial carbon balance. Wang et al. (2017) followed a somewhat different path, when coupling the RCM-CLM regional climate model (Wang et al. 2016) with a suite of socioeconomic models that account for the impacts of anthropogenic climate changes, socioeconomic developments and the response of cropland allocation to yield changes. Thus, the authors could simulate the effects of the associated land-use changes on climate incorporating the biophysical interactions between the land-surface and the atmosphere. This biophysical-socioeconomic modelling framework includes three different socioeconomic models. The first is the DSSAT crop modelling system, which includes three different types of crop growth models, each applicable for evaluating the productivity of a specific set of crops under any given climate. The second model is the IMPACT agricultural economics model. It is a partial equilibrium economic model, which among others provides estimates of demand for crops based on socioeconomic drivers and accounts for trade of agricultural commodities. The third model is the LandPro-Crop cropland projection model (Ahmed et al. 2016). It prioritizes the allocation of available land to different crop types based on existing land use, future crop yield and future demand for crops. The algorithm in this model achieves a balance between the demand and the supply of food at a country-level. The expansion of cropland in a country is driven by the future demand deficit for each crop, i.e. the difference between the future demand for a particular crop and its supply from present-day harvest areas. The algorithm then allocates available land to different crops in accordance with a set of pre-defined rules governing the conversion of naturally vegetated land or grassland to cropland.

The four model components are asynchronously coupled. To begin with, both the RCM and the IMPACT agricultural economics model are driven by the climate information originating from a global climate model. The RCM, using either prescribed (at the beginning of the simulation) or updated geographical distributions of land use and land cover from LandPro-Crop, simulates the meteorological forcing needed by the DSSAT crop model. DSSAT simulates the crop yield under the climate condition provided by the RCM (including bias correction) and IMPACT estimates the effective food demands under the climate conditions from the global climate model. The LandPro-Crop cropland projection model uses these two sources of information to update the geographical distributions of land use and land cover for the RCM. The asynchronous coupling approach had been chosen for two reasons. First, a synchronously coupled model that includes all the important components and processes with the desired level of complexity is currently not available and developing such a model that is able to achieve a balance between the different model components, each dealing with a specific aspect, is a challenging task. Second, synchronously coupled models encompass the risk of drifts due to feedbacks between the different sub-models enhancing the biases in all model components over time. In the asynchronous coupling approach, a bias in a particular sub-model can be corrected before the information is passed on to another model component, suppressing undesired feedbacks. However, the asynchronous coupling might induce inconsistencies between individual model components. A feature of the asynchronous coupling is that either an equilibrium or a transient approach can be adopted for the simulation. In the equilibrium approach, all simulations are done for a targeted future time slice only and the alternation between the four model components is done until the results converge. In the transient approach, each iteration of the model system represents a new time slice with an iteration time step of at least one year or several years. In practice, the iteration time step needs to be long enough for the land use activities to adapt to the impacts of climate change on crop yields. For the latter, the time scales of human decisions on adaptation measures are very important.

Wang et al. (2017) applied this biophysical-socioeconomic modelling framework to assess the future climate changes over West Africa in the middle of the 21st century in response to the changes in the atmospheric GHG concentrations and to LULCC in the region. Furthermore, the authors evaluated the contributions of climate change and of socioeconomic development on the agricultural land use changes in the area. The model was run adopting the equilibrium approach. The results suggested that the socioeconomic development would be the dominant driver of cropland expansion in the eastern part of West Africa and climate change would be the main driver in the western part of the region. For future climate conditions, it was found that the cropland expansions in the western part would lead to a decrease of summer precipitation in the area and to an increase in the downwind eastern part. The study also showed that over a substantial part of West Africa the magnitudes of the climatic changes induced by LULCC and the changes associated with the GHG changes were comparable. The uncertainties related to the driving global climate models were found to be small compared to the uncertainty associated with human decision-making with regard to land use or with international trade.

In an accompanying study, Ahmed et al. (2017) adopted the transient approach for a corresponding set of simulations to examine the transient dynamics of the system as well as the impact of the approach on the future climate projection over West Africa. The results showed that during the first half of the century the model simulated a monotonous increase of the food demand but pronounced temporal variations in the crop yields due to large climate variations. As such variations are not accounted for in the equilibrium approach, the transient approach resulted in generally faster expansions of cropland in order to adapt to the impacts of such variations. Despite these prominent differences between the two approaches with regard to LULCC associated with the simulated cropland expansions in West Africa, the projected future climate changes were very similar. That is, both approaches resulted in decreased summer precipitation in the western part of West Africa and increased precipitation in the eastern part, but the drying signal in the western part was weaker in response to the additional cropland expansion, when the transient approach was adopted. The authors, therefore, concluded that the equilibrium application of the modelling framework was likely adequate when assessing future climate changes, but when the climate impact on the agricultural sector needed to be assessed and potential mitigation or adaptation measures needed to be evaluated, incorporating the transient dynamics would be required.

Integrated human-earth system models

Van Vuuren et al. (2012) recognized fully coupled IAMs and ESMs as one way to improve the representation of the interactions between the human system and the earth system in a coupled modelling framework (see Chapter 9.1). Since 2012, there have been some efforts to develop such integrated human-earth system models. Calvin and Bond-Lamberty (2018) reviewed the state of the science behind such modelling systems and discussed the future directions for developing such systems. The scientific literature considered in their review (19 scientific publications) revealed various feedbacks with the potential to alter both the human and earth systems. The authors found, however, significant uncertainties related to the results of these studies, with the number of truly integrated studies being rather small. They emphasized the need for more research, including more models and more studies, to robustly quantify the sign and the magnitude of various kinds of feedbacks between the human and earth systems. As integrating these two systems in a coupled modelling framework is a very complex task and operating such models rather costly, researchers should carefully assess the costs and benefits of doing so with respect to the objective of the study and possibly employ a less advanced approach (see Chapter 9.1).

As a step towards a coupled modelling framework of the human and the earth system, Bond-Lamberty et al. (2014) employed a reduced version of an integrated human-earth system model. The goal was to optimize the coupling between the land component of the Community Earth System Model (CESM), i.e. CLM, and the GCAM integrated assessment model with focus on the terrestrial carbon cycle. The coupling between these two different types of models is challenging because of the substantially different purposes and underlying principles of the two types of models. Testing a number of possibilities, the authors identified the net primary production and the heterotrophic respiration outputs from CLM as the most robust proxy variables to properly represent carbon in CGAM. Collins et al. (2015) presented a full version of this integrated human-earth system model (iESM), including CESM as a whole (except for the ocean component) as well as the GCAM IAM and the GLM global land-use model (Fig. 9.3). GCAM is forced with the atmospheric CO_2 concentration and the climate forcing from the atmospheric component of CESM (CAM) and with the climatic effects on the carbon stocks and crop yields (i.e. the net primary production and the heterotrophic respiration) from CLM. GCAM returns emissions from fossil fuels and industry (i.e. GHGs, short-lived species and aerosols) to CAM and land-use and land-cover changes via GLM to CLM. The synchronous coupling between the IAM and the ESM is done every 5 years, the time step of GCAM.

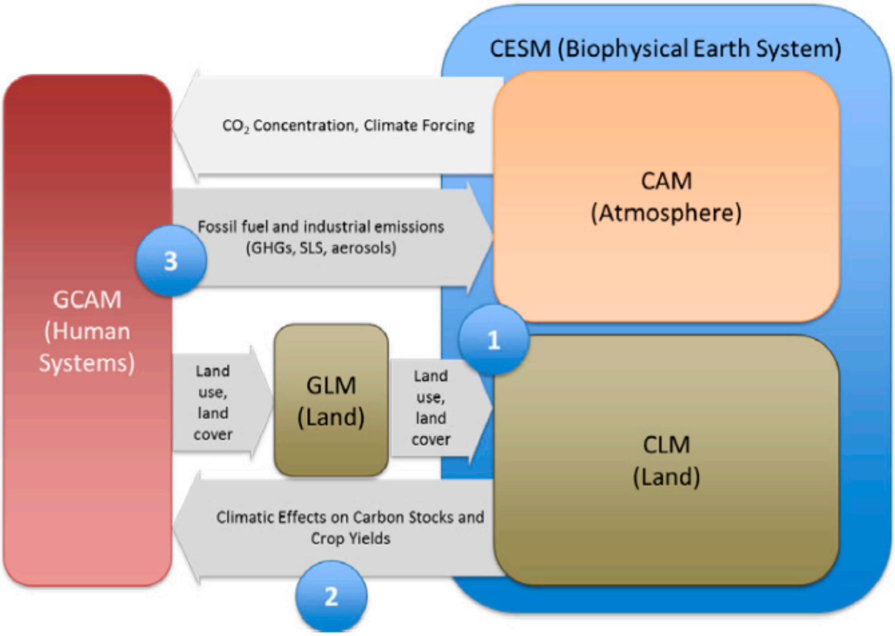


Fig. 9.3: Schematic of the integrated Earth system model (iESM) showing its major component models GCAM, CESM, and GLM as well as the two-way connections between these models. References to the individual models are given in the original publication. From Collins et al. (2015)

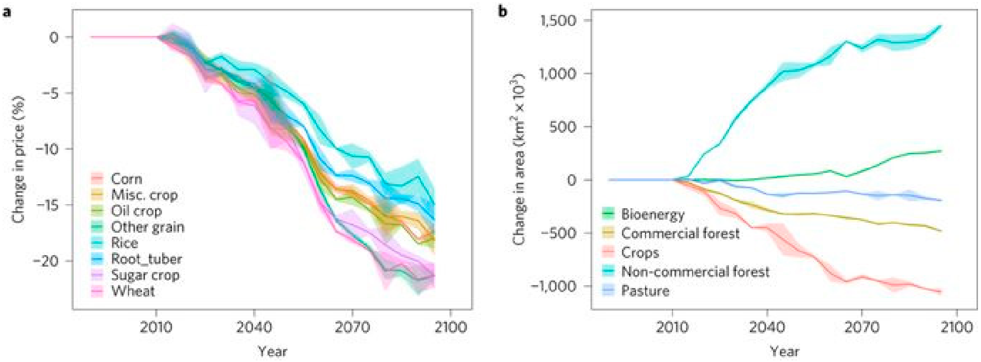


Fig. 9.4: (a) Percentage change in global average crop price, relative to the asynchronous one-way coupling simulation, for each major crop type. **(b)** Global total change in land cover summarized by major land-use/land-cover types, relative to the asynchronous one-way coupling simulation. For each aggregated crop type or land-cover type, the solid coloured line shows the mean of two ensemble simulations, while the shaded region of matching colour shows the range of values from the two ensemble members. From Thornton et al. (2017)

Thornton et al. (2017) applied the iESM integrated modelling framework to investigate the effects of including the feedbacks between the human and earth system on the projected future changes in terrestrial ecosystems over the 21st century in accordance with the RCP4.5 scenario. The authors concluded that feedbacks between terrestrial ecosystems and the human system could significantly alter the anthropogenic climate forcing by causing changes in land-use and energy activities. These changes, then, affect the carbon stocks of the land and the atmosphere and the trajectories of the fossil fuel emissions. In particular, the land areas used for crops were found to be reduced, while the areas with non-commercial forests were extended (Fig. 9.4b). The projected increase in the global crop price in response to the mitigation policy that applies a cost to carbon emissions, is markedly (12-25%) reduced when the feedback from the human system is included (Fig. 9.4a). The decline in crop prices is due to higher productivity that reduces the demand for cropland and, thus, lowers the competition for cropland.

10. Discussion

The synthesis makes use of three types of methodology, i.e. a review of the scientific literature, engagement with stakeholders and modelling tools (see Chapter 4). For the review of the scientific literature, we have scrutinized a large fraction of the existing scientific literature related to the subject of the synthesis. Although this approach is somewhat subjective, we think that we have captured the majority of the relevant scientific publications. Many of them have been included in the synthesis (see the list of references) and more can be found in the enclosed list of more than 200 scientific publications that have been scrutinized for the synthesis (see Electronic supplement E5). These publications have been categorized, according to the various aspects dealt with in the synthesis. We have also searched two different databases (i.e. Web of Science and Google Scholar) for scientific publications on the biophysical effects of land-use and land-cover changes on climate (see Chapter 5.1 and Electronic supplements E1-E4). The results of these searches revealed numerous scientific publications, but they provided less appropriate scientific publications than our subjective search, because the searches gave numerous studies on the local processes at a specific site or for a particular type of ecosystem. Note also that the synthesis includes a wide range of related aspects other than the biophysical interactions between the land surface and the atmosphere, which have not been specified when searching the two databases.

In the synthesis, we have focussed on published work. In preparation to CMIP6, however, the major climate modelling centres as well as the EC-Earth consortium have further developed their modelling tools, resulting in a new generation of ESMs (e.g. Mauritsen et al. 2019, Sellar et al. 2019, Danabasoglu et al. 2020, Döscher et al. 2020 [in preparation on EC-Earth 3]). These developments cover a wide range of aspects, e.g. improved representation of physical, chemical and biological processes, inclusion of additional processes, inclusion of anthropogenic LULCC, improved dynamics and physical parametrizations in the physical climate model, increased resolutions, etc. Some of these developments will affect the coupling and feedbacks between the land surface and the atmosphere in general and the biophysical effects of LULCC on climate in particular. Thus, studies using the new generation of ESMs will, hopefully, give a more comprehensive and/or more robust picture of the biophysical (as well as the biogeochemical) effects of anthropogenic LULCC.

We have involved stakeholders from the affected sectors and policymakers in the synthesis during a workshop centred on bioenergy and the recent report on the sustainable production of bioenergy "Bioenergi på rätt sätt" (see Chapter 7.1). The main two sectors that are expected to contribute to changes in land use and land cover in response to the Swedish national climate policy, agriculture and the forestry sector, were well represented at the workshop. The discussions at the workshop indicated that it is currently unclear how the ambitious goals of the Swedish climate policy will affect these two sectors. This is mainly due to the fact that the legal and policy instruments to achieve these goals still have to be designed and implemented. Furthermore, knowledge about the effects of such instruments is very limited. Hence, it is presently not clear which LULCC will be associated with the new Swedish climate policy.

We have presented modelling tools that have been developed and applied in Sweden for simulating terrestrial ecosystems and the interactions between the land surface and the atmosphere at a regional scale (see Chapter 4.3). We also give several examples of scientific questions that have been addressed employing these models. This presentation indicates that the basic modelling tools for assessing the biophysical effects of anthropogenic LULCC associated with particular climate policies for Sweden or with specific future emission scenarios (see Chapter 8.2) are already available. In their current forms, these modelling tools include only limited interactions with the human system, meaning that they typically do not consider human decisions and their effects on the state of the land surface or on the GHG emissions from energy production. Exceptions include the representation of land management decisions for croplands and forestry in the "managed land" version of LPJ-GUESS, the regional and global ESMs it is coupled to, as well as the integrated assessment framework presented by Engström et al. (2017), which incorporates feedbacks between human land use decisions, economic growth and energy use, and the land carbon cycle via linkages between component models. Such interactions between the human and the earth system would be needed to provide the most realistic projections of future climate change (see Chapter 9.3).

We have put more emphasis on forests and the forestry sector than on agriculture, as forests and forestry are likely to play a major role in Sweden's efforts to achieve the goals of having zero net emissions of GHG in 2045 and negative emissions thereafter (see Chapter 6.2).

11. Conclusions

The PA aims at holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels. Keeping these thresholds would significantly reduce the risks and impacts of climate change (IPCC 2018). In accordance with the PA and the SDGs of the United Nations, the Swedish Government proposed the legal framework for a Swedish national climate policy. The policy entered into force at the beginning of 2018, after its acceptance by the Swedish Parliament. The aim of this pioneering policy is that Sweden should have zero net emission of GHGs by 2045 and negative emissions thereafter. Achieving the goals of the PA and of the Swedish national climate policy requires climate mitigation through emission reductions and the large-scale deployment of negative emissions techniques, resulting in a net removal of GHGs from the atmosphere. Envisaged techniques include bioenergy as well as re- and afforestation to sequester carbon in biomass and soils. These techniques are associated with considerable LULCC, affecting climate through various types of interactions between the land surface and the atmosphere, i.e. biogeochemical and biophysical interactions. The biogeochemical interactions control the exchanges of carbon between the atmosphere and terrestrial ecosystems, the release of CH_4 and N_2O from terrestrial ecosystems, the release of aerosols at the land surface and the emissions of BVOC by the vegetation. The biophysical interactions govern the exchanges of momentum, heat and water between the land surface and the atmosphere. While the sequestration of carbon in terrestrial ecosystems reduces the atmospheric concentration of CO_2 and, thus, the rate of global warming, the impacts of the biophysical interactions and of the other biogeochemical interactions associated with LULCC on temperatures are not as clear and vay in magnitude, and sometimes sign, both regionally and seasonally. They can either further reduce the rate of warming or offset the effects of the reduced atmospheric CO_2 concentration by increasing temperatures locally or regionally. In this synthesis we, therefore, evaluate the importance of biophysical interactions between the land surface and the atmosphere for the states of climate and terrestrial ecosystems at regional scale. This contributes to an improved and comprehensive understanding of the feasibility and the implications of the goals formulated in the Swedish national climate policy.

Governing the exchanges of momentum, heat and water between land and the atmosphere, the biophysical effects of LULCC influence the dynamics of the ABL, i.e. the wind speed, temperature, humidity and precipitation, and the atmospheric radiative balance. One of the primary biophysical impacts of vegetation is through the surface albedo, determining the radiative balance at the land surface and, hence, the turbulent fluxes of energy at the land surface. Forests have a lower surface albedo than pasture and cropland, particularly when these are covered with snow, and the surface albedo is somewhat lower for coniferous than for deciduous forest. The increased absorption of solar radiation at the land surface associated with decreased surface albedo enhances net radiation, leads to strong turbulent fluxes of heat and can warm the surface. Furthermore, the surface heating of the ABL increases, possibly enhancing precipitation. Vegetation also determines the roughness length, with trees being aerodynamically rougher than grass and crops. Increased roughness length due to deforestation, for instance, results in weak turbulent fluxes of heat and water and, thus, can ameliorate particularly warm and dry conditions in the ABL. Trees also have a larger area of leaves and deeper roots than grass and crops, so that they are able to transpire more water. The high evapotranspiration rate of trees cools the land surface, moistens the ABL and, possibly, initiates cloud formation and precipitation.

Historical and recent LULCC have had strong effects on local and regional climate, in particular near-surface temperatures, through biophysical interactions. In the temperate zone of the Northern Hemisphere, the quality of these effects on near-surface temperatures depends on the geographical latitude. Both in North America and Eurasia, afforestation leads to decreased mean temperatures in the northern part of the regions but warmer temperatures in the southern parts, with transitions zones in between. In contrast, afforestation causes increased mean temperatures to the north but colder temperatures to the south. In the southern parts, it is mainly the daily maximum temperatures that are affected by the changes in the land cover, with marked decreases associated with more open land and increases in relation to forests. In the northern parts, on the other hand, it is primarily the daily minimum temperatures that are influenced, with pronounced increases over areas with more open land and decreases over areas with forests. In the boreal zone, however, the situation is more complex. Here, forests have a warming effect in late winter and early spring but a cooling effect during the rest of the year. The difference between the boreal and temperate zones is related to the lower surface albedo with the masking of snow by the forest canopy.

Historical LULCC also affect climate through biogeochemical interactions, including the exchange of carbon between the atmosphere and the terrestrial ecosystems. Thus, the historical anthropogenic deforestation has led to a warming of global mean temperatures forced by the increased level of atmospheric CO_2. In contrast to the biophysical interactions, this biogeochemical effect influences climate at global and regional scales, increasing the global mean temperatures and altering large-scale circulation patterns. Simulations with global climate models, which have been used to separate the biophysical and the biogeochemical effects on climate, show that the biophysical effects of historical LULCC in North America and Eurasia have an overall cooling effect in these regions, particularly in spring and summer. Thus, the biophysical effects counteract the overall warming trend due to increased climate forcing, including the CO_2 emissions from the deforestation.

Current climate models capture by and large the biophysical effects of LCC on climate and, hence, are suitable for simulating the effects of historical or projected future changes in land use and land cover. In contrast to observations, however, model simulations also include the non-local biophysical effects of LULCC as changes in the large-scale atmospheric circulation are incorporated. It was found that such non-local effects can partly account for the differences between observations and climate simulations. The majority of current ESMs only incorporate the carbon cycle to represent the biogeochemical interaction between the land surface and climate, while the effects of primary and secondary aerosols resulting from vegetation fluxes (e.g. BVOC) on climate are not generally considered. The climate models are characterized by great variability in the sign and the magnitude of the carbon feedbacks on climate that can be attributed to uncertainties in the representation of the land carbon cycle, but is also significantly affected by inherent biases in the physical climate model.

Forests and forestry are expected to play a very important role for reaching the goals of zero net emissions of GHGs by 2045 in accordance with the Swedish national climate policy. Re- and afforestation can increase the carbon storage in forest ecosystems and can provide the additional wood biomass that is needed to replace fossil fuels or to be exported as saw timber. As clear-cutting of even-aged stands is the most common form of forest management in Sweden at the moment, extracting more biomass from Swedish forests decreases the carbon storage in forest ecosystems. This loss of carbon is further enhanced when more forest residues (i.e. slash and stumps) are removed after felling to provide additional bioenergy.

Re- and afforestation effect climate in Sweden through biogeochemical and biophysical interactions (see Fig. 5.7). The decrease in surface albedo is the only effect that leads to a warming of the near-surface temperatures, while all the other effects lead to a cooling and, hence, mitigate the warming associated with climate change. The magnitude of the overall cooling in Sweden associated with re- and afforestation and longer rotation times depends on the significance of the warming effect compared to the cooling from the other biophysical and biogeochemical effects. Clear-cutting, however, has the opposite impacts with all biophysical and biogeochemical effects leading to a warming, except for the increased surface albedo resulting in colder temperatures. The overall significance of the effects of re- and afforestation depends on the projected climatic changes in Sweden. Increasing near-surface temperatures and reduced precipitation during summer are expected to weaken the cooling effects of afforestation in Sweden.

Scenarios of future climate forcing, including GHG emissions, in accordance with different pathways of future development also specify future land use. Depending on the narrative that a specific pathway is based on, land use can change considerably, either, for example, by transforming natural land and forests into cropland and pasture in a scenario with strong fossil-fuelled development or by transforming pasture into forests and natural land in a scenario with high sustainability. Given the marked biophysical effects of historical LULCC, the future land-use changes need to be taken into account in future climate projections. Also for Sweden the different narratives of development pathways lead to distinct patterns of land-use changes, even with opposite future changes for particular landscapes in certain regions. The SSP marker scenarios agree on an overall reduction of secondary forest in Sweden during the 21st century, except for increases in some parts of central Sweden for some of the scenarios, and a reduction of non-forested primary land. In some of the scenarios, the areas with cropland are increased, while in others the areas with managed pasture and rangeland are increased. The marker scenarios, however, are only one realisation of the different scenarios, as they have been selected from a variety of scenarios for each of the narratives and the radiative forcing, originating from different IAMs. The differences between the land-use changes simulated by different IAMs for a particular scenario are as large as the deviations between the different marker scenarios.

Standard modelling tools are currently able to incorporate anthropogenic land-use and/or land-cover changes. In IAMs, such changes are simulated, while they are prescribed in DGVMs and global and regional ESMs, mostly incorporated into the model components that represent the land surface and/or vegetation. These ESMs, however, do not explicitly include human behaviour and decision-making and, hence, the associated feedbacks between the changes in land use, management and land cover and climate. These processes need to be represented in ESMs in order to incorporate dynamic adaption or mitigation measures in response to the simulated climate changes and, thus, arrive at more realistic future climate projections.

Recent model developments have started to address shortcomings in current standard modelling tools. One such development is to include human decisions on, for instance, the production of energy and on the usage of cropland for food production and bioenergy, in IAMs. The next step of development is to couple a physical climate model (either RCM or GCM) with a suite of socioeconomic models, i.e. advanced land-use and food system models. The most comprehensive modelling tool with an improved representation of the interactions between the human and the earth systems is an integrated human-earth system model, fully coupling an IAM and an ESM. Such an integrated modelling system has recently been established and successfully applied to investigate the impacts of including feedbacks between the human and the earth system on the potential future changes of terrestrial ecosystems. It has been found that such feedbacks significantly alter the anthropogenic climate forcing by changing land-use and energy activities and thus, the carbon stocks and the trajectories of fossil fuel emissions. Integrating these two systems in a coupled modelling framework, however, is a complex task and operating such models is rather costly. Therefore, one needs to carefully assess the costs and benefits of applying an integrated human-earth system model with respect to the objective of the study in question and possibly employ a less advanced approach.

12. Recommendations for future research

Anthropogenic LULCC and their effects on climate through biophysical and biogeochemical interactions with the atmosphere will play an important role for the future climate, both because land use and land cover are affected by climate change and because adaptation and mitigation measures influence the land surface. Hence, future research needs to incorporate anthropogenic LULCC and its impacts on climate in the most comprehensive way possible. This includes not only the physical, chemical and biological mechanisms operating in the earth system but also the socioeconomic processes affecting human systems and, thus, shaping societal changes through governance. In the following, we make a number of recommendations for future research supporting the development of a comprehensive integrated modelling framework of the interactions between the earth system and the human system. These recommendations are grouped in four broad categories, i.e. the representation of processes, model developments, land-use scenarios and the relevance for policies. Most of the suggestions are based on this synthesis and some are inspired by the scientific publications that have been scrutinized during the preparation of the synthesis.

Representation of processes: The interactions between terrestrial ecosystems and the atmosphere as well as the two components of the earth system themselves are governed by a range of physical, chemical and biological processes. For some of these processes, the theoretical understanding needs to be advanced in order to better represent them in modelling tools, either in an improved approach or incorporated for the first time. In the development and application of terrestrial ecosystem models, there has been a tendency to focus on the carbon cycle. This focus needs to be extended to also include the methane and the nitrogen cycles and other nutrients such as phosphorous, given the importance of nutrient interactions for the carbon cycle, and BVOC because of their potentially distinct climate impact. There has also been a tendency to focus on near-surface temperatures at the expense of other aspects of climate that are equally important for terrestrial ecosystems, i.e. precipitation and soil moisture. The processes governing the interactions between the land surface and the atmosphere in relation to these climate variables need to be evaluated and their representations in modelling tools needs to be improved. A further need is the proper and improved representation of disturbance events on ecosystem form and function. Disturbances such as wildfires, storm events/damage, insect and animal herbivory influence the biophysical and biogeochemical interactions of ecosystems with the atmosphere.

Coupled model developments: The coupling between the human system and the earth system to better incorporate human decisions in climate projections has started. Presently, the number of aspects that are considered in socioeconomic model components is limited. Therefore, the range of aspects incorporated in the socioeconomic model components, e.g. sectors or policies, needs to be extended. To meet the specific requirements for Sweden, the development of a new integrated RESM is needed. To begin with, the RESM needs to represent all the ecological and the physical processes that are required to incorporate the information provided from the socioeconomic model component. Then the socioeconomic model that deals with the sectors and policies that are important for the country needs to be interactively coupled to represent the dynamics of and the feedbacks with the human system. In order to be used at a country level, this integrated modelling framework needs to be applicable at rather fine spatial scales. Such an integrated RESM would provide a proving ground for model development and for assessing the impacts of incorporating specific aspects of the human system that are typically applied at regional or country level. The coupling between the human system and the earth system will increase the reliability of climate scenarios, but it will also lessen the uncertainty originating from the differences between individual IAMs.

Land-use scenarios: Both adaptation to the impacts of climate change and mitigation of climate change have strong impacts on land use (including management practices) and land cover. Although guided by international policies, it is mainly the national climate policies and their implementation through legal and policy measures that determine LULCC at a country level. In order to be able to realistically assess the impacts of adaptation and mitigation measures at a national level, specific scenarios of LULCC for Sweden are needed. Community scenarios, such as the LUH2 data for the SSPs, could serve as an overall guideline, but require comprehensive validation against baseline land cover data for Sweden, and additional regional details need to be added. As adaptation and mitigation measures are generally effective at very small spatial scales, i.e. at farm level, forest level or landscape level, a methodology needs to be developed to upscale the local information on LULCC to the scale of a grid cell in the climate model. Furthermore, there are some general issues with the development of LULCC scenarios that need to be addressed in order to reduce the uncertainty inherent to these scenarios. There is, for instance, the issue of the harmonization of LULCC scenarios based on different IAMs, which heavily depend on the kind of observational data and the land-use model applied. LULCC scenarios would be more realistic if they included explicit information on land-use transitions rather than annual updates of land-use states.

Relevance for national policies: Given the strong impact of LULCC on climate via biophysical interactions, a comprehensive assessment of the changes in land use and land cover due to adaptation and mitigation measures complying with the Swedish national climate policy is needed. Including the biophysical effects and biogeochemical effects other than those relating only to CO_2 exchange and land carbon storage, e.g. methane fluxes, nitrogen and other nutrient cycling and BVOC exchange, will give a better estimate of the overall effects of the climate policy and reduce the uncertainty associated with neglecting these important interactions. Furthermore, the national climate policy cannot be considered independently but needs to be related to other national policies governing, for instance, biodiversity, water quality or food security. All policies affect land use and land cover in various ways, possibly leading to conflicting measures and, thus, competition for the land. Given the limited land resources and potential conflicting goals, the effects of different policies on LULCC need to be considered as a whole. This will require collaboration between different disciplines, often focussing on a specific area or a particular aspect related to one of the national policies. A realistic estimate of the fraction of land actually available for adaptation and mitigation measures will be crucial for a realistic assessments of the impacts of the associated LULCC on climate.

The Swedish context: The scientific knowledge and some of the model components of an envisaged integrated RESM, and expertise in their development and application, are already available in Sweden. Also, Sweden holds the capacity and capability needed to extend the utility and to overcome the limitations of available modelling tools. Given the focus on forests and forestry in Sweden, it is important to include aspects that are particularly relevant. That are, for instance, changes in forest management to adapt to climatic changes, i.e. heatwaves, drought or storms, or to climate-induced changes in the risks of fire or insect attacks. But also climate-induced changes in the species composition, with broadleaf species migrating into Swedish ecosystems. In accordance with Swedish national environmental policy, forest management has to ensure the conservation of biodiversity. Increasing the production of wood biomass and intensifying the extraction of forest residues in accordance with the Swedish national climate policy, however, could have adverse effects on biodiversity. Therefore, it is important to reconcile both policies when implementing measures to reach the Swedish goal of zero net emissions of GHGs in the coming decades.

We do not consider this list of recommendations as exhaustive. Addressing some of them will lead to an improved understanding of what changes in land use and land cover associated with adaptation to the impacts of climate change and the mitigation of climate change might entail and give better estimates of the overall effects of these changes, including synergies and trade-offs. The improved understanding will then form the basis for designing climate and other policies and their implementation in various sectors.

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Glossary

Bioenergy with carbon capture and storage (BECCS): Bioenergy with carbon capture and storage is the process of extracting bioenergy from biomass and capturing and storing the carbon, thereby removing it from the atmosphere.

Biogeochemical effects: Processes through which land affects climate, excluding biophysical effects. These processes include changes in net emissions of carbon dioxide towards the atmosphere, net emissions of aerosols (mineral and organic), ozone deposition on ecosystems, and net emissions of biogenic volatile organic compounds and their subsequent changes in atmospheric chemistry.

Biophysical effects: The range of physical processes through which land affects climate. These processes include changes in hydrology (e.g. water vapour fluxes at the land/atmosphere interface), heat exchanges via convective fluxes (latent and sensible), radiation (solar and infrared, absorbed and emitted), and momentum (e.g. affecting wind speed).

Climate model: A climate model is a numerical representation of the climate system based on the physical, chemical and biological properties of its components, their interactions and feedback processes and accounting for some of its known properties. The climate system can be represented by models of varying complexity; that is, for any one component or combination of components a hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical or biological processes are explicitly represented, or the level at which empirical parametrizations are involved.

Cumulative radiative forcing (CRF): The cumulative radiative forcing is defined as the radiative forcing over a specified period of time.

CO_2-equivalent (CO_2-eq): A carbon dioxide equivalent or CO_2-equivalent is a metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential (GWP), by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential. For example, the GWP for methane is 28-36 and for nitrous oxide it is 265-298.

Dynamic global vegetation model (DGVM): A Dynamic global vegetation model is a numerical model of terrestrial ecosystems that simulates shifts in potential vegetation and its associated biogeochemical and hydrological cycles as a response to shifts in climate.

Earth system model (ESM): An Earth system model is a coupled atmosphere–ocean general circulation model in which a representation of the carbon cycle is included, allowing for interactive calculation of atmospheric carbon dioxide or compatible emissions. Additional components (e.g. atmospheric chemistry, ice sheets, dynamic vegetation, nitrogen cycle, but also urban or crop models) may be included as well.

Integrated assessment model (IAM): Models that integrate knowledge from two or more domains into a single framework. They are one of the main tools for undertaking integrated assessments. One class of IAM used in respect of climate change mitigation may include representations of: multiple sectors of the economy, such as energy, land use and land use change; interactions between sectors; the economy as a whole; associated greenhouse gas emissions and sinks; and reduced representations of the climate system. Another class of IAM additionally includes representations of the costs associated with climate change impacts, but includes less detailed representations of economic systems.

Land cover: Land cover is defined as the sum of all land surface properties at a given location, and it is typically described by vegetation and soil characteristics at that location. Land cover is often characterized by broad classes (e.g. forest, grassland or bare ground), which can be sub-divided into more detailed classes (e.g. deciduous forest, coniferous forest or mixed forest).

Land use: Land use relates to the purposes or functions that humans have assigned to a location and how humans interact with the land, and it is typically characterized by broad classes (e.g. forestry, grazing or cropping). Land management refers to the land-use practices that are applied within these broad classes (e.g. sowing, fertilizing, harvesting, thinning or clear-cutting).

Land-use and land-cover change (LULCC): Land-use change (LUC) refers to either conversion among broad land-use classes (e.g. agricultural expansion) or shift in land management within these classes (e.g. agricultural intensification). Both kinds of LUC can result in land-cover change (LCC), either in a land-cover transition from one broad class to the other (e.g. forest loss) or in land-cover modifications, i.e. slight changes in ecosystem properties (e.g. forest degradation).

Land use, land-use change and forestry (LULUCF): In the context of national greenhouse gas (GHG) inventories under the United Nations Framework Convention on Climate Change, land use, land-use change and LULUCF is a GHG inventory sector that covers anthropogenic emissions and removals of GHG in managed lands, excluding non-CO_2 agricultural emissions. “Anthropogenic” land-related GHG fluxes are defined as all those occurring on “managed land”, i.e. “where human interventions and practices have been applied to perform production, ecological or social functions”.

Paris Agreement (PA): The Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) was adopted on December 2015 in Paris, France, at the 21st session of the Conference of the Parties to the UNFCCC. One of the goals of the PA is “Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels”, recognising that this would significantly reduce the risks and impacts of climate change. Additionally, the PA aims to strengthen the ability of countries to deal with the impacts of climate change.

Radiative forcing (RF): Radiative forcing is the change in the net, downward minus upward, radiative flux (expressed in $W\ m^{-2}$) at the tropopause or top of atmosphere due to a change in an external driver of climate change, e.g. a change in the concentration of carbon dioxide or the output of the sun.

Regional climate model (RCM): A Regional climate model is a physical climate model at higher resolution over a limited area. Such models are used in downscaling global climate results over specific regional domains.

Regional earth system model (RESM): A Regional earth system model is an earth system model based on a regional climate model used for downscaling global climate results over specific regional domains.

Representative concentration pathway (RCP): Scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases and aerosols and chemically active gases, as well as land use/land cover. The word representative signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics. The term pathway emphasizes that not only the long-term concentration levels are of interest, but also the trajectory taken over time to reach that outcome.

Shared socioeconomic pathway (SSP): Shared socio-economic pathways were developed to complement the Representative concentration pathways with varying socioeconomic challenges to adaptation and mitigation. Based on five narratives, the SSPs describe alternative socioeconomic futures in the absence of climate policy intervention, comprising sustainable development (SSP1), regional rivalry (SSP3), inequality (SSP4), fossil–fuelled development (SSP5), and a middle-of-the-road development (SSP2).

Electronic supplements

E1: List of scientific articles (including abstracts) identified in the Web of Knowledge database

E2: List of review papers (including abstracts) identified in the Web of Knowledge database

E3: List of scientific articles (including abstracts) identified in the Web of Knowledge database before 2000

E4: List of scientific articles identified in the Google Scholar database

E5: List of scientific publications scrutinized during the preparation of the synthesis, including a categorization of the publications