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Land-atmosphere interactions and regional Earth system dynamics due to natural and anthropogenic vegetation changes

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Minchao Wu

LUND UNIVERSITY

DOCTORAL DISSERTATION

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Abstract

Observation and modelling studies have indicated that the global land surfaces have been undergoing significant changes in the past few decades, driven by both natural and anthropogenic factors, such as changes in ecosystem productivity, fire and land use. Land surface changes can potentially influence local and regional climate through land-atmosphere interactions. Continued greenhouse gas emissions and current socioeconomic trends are expected to drive further land cover changes in the future, thus further understanding of land-atmosphere interactions including different feedback mechanisms is necessary to understand how future climate change will continue unfolding. Land-atmosphere interactions vary under different conditions. The strength of local land-atmosphere interactions depends on the capabilities of different land covers to control surface energy and mass exchanges, including latent and sensible heat, water and carbon. Local feedbacks can also influence regional to global climate, such as circulation changes that affect regional energy and moisture transport, or cloud cover that affects incoming radiation. Regional Earth system models (RESMs) with high resolution dynamical downscaling approaches and incorporating individual-based vegetation dynamics add value to the traditional global climate modelling studies for regions with highly complex topography or/and pronounced seasonal water deficits, potentially allowing for more refined land-atmosphere interactions studies thanks to more realistic vegetation dynamics and biophysical feedbacks, more accurate regional climate dynamics and overall richer spatial detail.

In this thesis, I investigated regional land surface changes due to natural and anthropogenic vegetation changes and their impacts on land-atmosphere interactions, by applying a dynamical downscaling approach with RCA-GUESS, a RESM that couples the Rossby Centre regional climate model RCA4 to LPJ-GUESS, an ecosystem model that combines an individual-based representation of vegetation structure and dynamics with process-based physiology and biogeochemistry. Europe, Africa and South America were chosen as research domains. In the land surface study based on LPJ-GUESS simulations, I showed that future changes in the fire regime over Europe, driven by climate and socioeconomic change, were important for projecting future land surface changes. Fire-vegetation interactions and socioeconomic effects emerged as important uncertainties for future burned area. My study on land-atmosphere interactions based on RCA-GUESS simulations indicated that the hydrological cycle in the tropics was sensitive to land cover changes over semi-arid regions in Africa, and that biophysical feedbacks were important through their modulation of regional circulation patterns. A study based on the analysis of empirical datasets and CMIP5 ESMs outputs revealed that simulated climate biases are the main cause of model-data discrepancies. Models and data shared a marked hydrological relationship that suggested that decreased precipitation and land use change constituted the largest threats to the future Amazon forest. A study based on RCA-GUESS simulations with a realistic land use scenario identified both positive and negative impacts of land use on natural ecosystem productivity in the Amazon through its effects on the local and the regional climate.

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A doctoral thesis at a university in Sweden is produced either as a monograph or a collection of papers. In the latter case, the introductory part constitutes the formal thesis, which summarises the accompanying papers already published or manuscripts at various stages (in press, submitted or in preparation).

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To Yuan, for a life together

To Anneli and Benjamin, for all fun they have given to me

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I. Wu, M., Knorr, W., Thonicke, K., Schurgers, G., Camia, A., and Arneth, A.: Sensitivity of burned area in Europe to climate change, atmospheric CO_2 levels, and demography: A comparison of two fire-vegetation models, *Journal of Geophysical Research: Biogeosciences*, 120, 2256-2272, doi:10.1002/2015JG003036, 2015.

II. Wu, M., Schurgers, G., Rummukainen, M., Smith, B., Samuelsson, P., Jansson, C., Siltberg, J., and May, W.: Vegetation–climate feedbacks modulate rainfall patterns in Africa under future climate change, *Earth System Dynamics*, 7, 627-647, doi:10.5194/esd-7-627-2016, 2016.

III. Ahlström, A., Canadell, J.G., Schurgers, G., Wu, M., Berry, J.A., Guan, K., Jackson, R.B.: Hydrologic resilience and Amazon productivity. *Submitted*.

IV. Wu, M., Schurgers, G., Ahlström, A., Rummukainen, M., Miller, P.A., Smith, B., May, W.: Impacts of land use on climate and ecosystem productivity over the Amazon and the South American continent. *Submitted*.

Contributions

I. MW anticipated the study design and led the writing. MW performed the LPJ-GUESS simulations, evaluated model performance, and compiled simulation results into the manuscript. All authors contributed to the paper writing.

II. MW led the study design and the writing. MW performed the model simulations, conducted model evaluation, carried out the data analysis, and compiled results into a manuscript. All authors contributed to the paper writing.

III. MW performed model experiments for investigating land use impacts, and commented on the manuscript.

IV. MW led the study design and the writing. MW conducted model development, performed the model simulations, evaluated model performance, carried out the data analysis, and compiled results into a manuscript. All authors contributed to the paper writing.

Abbreviations

AGB	Above ground biomass
CMIP5	Coupled Model Intercomparison Project Phase 5
CORDEX	Coordinated Regional Climate Downscaling Experiment
DGVM	Dynamic global vegetation model
ESM	Earth system model
ET	Evapotranspiration
GCM	Global climate model
GHG	Greenhouse gas
GPP	Gross primary production
IPCC	Intergovernmental Panel on Climate Change
LAI	Leaf area index
LPJ-GUESS	Lund-Potsdam-Jena General Ecosystem Simulator
LSS	Land surface scheme
LULCC	Land use and land cover change
NPP	Net primary productivity
PFT	Plant functional type
RCA	Rossby Centre regional atmospheric model
RCM	Regional climate model
RCP	Representative Concentration Pathway
RESM	Regional Earth system model
SSP	Shared Socioeconomic Pathway
SST	Sea surface temperature
WUE	Water use efficiency

Abstract

Observation and modelling studies have indicated that the global land surfaces have been undergoing significant changes in the past few decades, driven by both natural and anthropogenic factors, such as changes in ecosystem productivity, fire and land use. Land surface changes can potentially influence local and regional climate through land-atmosphere interactions. Continued greenhouse gas emissions and current socioeconomic trends are expected to drive further land cover changes in the future, thus further understanding of land-atmosphere interactions including different feedback mechanisms is necessary to understand how future climate change will continue unfolding. Land-atmosphere interactions vary under different conditions. The strength of local land-atmosphere interactions depends on the capabilities of different land covers to control surface energy and mass exchanges, including latent and sensible heat, water and carbon. Local feedbacks can also influence regional to global climate, such as circulation changes that affect regional energy and moisture transport, or cloud cover that affects incoming radiation. Regional Earth system models (RESMs) with high resolution dynamical downscaling approaches and incorporating individual-based vegetation dynamics add value to the traditional global climate modelling studies for regions with highly complex topography or/and pronounced seasonal water deficits, potentially allowing for more refined land-atmosphere interactions studies thanks to more realistic vegetation dynamics and biophysical feedbacks, more accurate regional climate dynamics and overall richer spatial detail.

In this thesis, I investigated regional land surface changes due to natural and anthropogenic vegetation changes and their impacts on land-atmosphere interactions, by applying a dynamical downscaling approach with RCA-GUESS, a RESM that couples the Rossby Centre regional climate model RCA4 to LPJ-GUESS, an ecosystem model that combines an individual-based representation of vegetation structure and dynamics with process-based physiology and biogeochemistry. Europe, Africa and South America were chosen as research domains. In the land surface study based on LPJ-GUESS simulations, I showed that future changes in the fire regime over Europe, driven by climate and socioeconomic change, were important for projecting future land surface changes. Fire-vegetation interactions and socioeconomic effects emerged as important uncertainties for future burned area. My study on land-atmosphere interactions based on RCA-GUESS simulations indicated that the hydrological cycle in the tropics was sensitive to land cover changes over semi-arid regions in Africa, and that biophysical feedbacks were important through their modulation of regional circulation patterns. A study based on the analysis of empirical datasets and CMIP5 ESMs outputs revealed that simulated climate biases are the main cause of model-data discrepancies. Models and data shared a marked hydrological

relationship that suggested that decreased precipitation and land use change constituted the largest threats to the future Amazon forest. A study based on RCA-GUESS simulations with a realistic land use scenario identified both positive and negative impacts of land use on natural ecosystem productivity in the Amazon through its effects on the local and the regional climate.

Sammanfattning

Observationer och modelleringsstudier har visat att den globala markytan har genomgått betydande förändringar under de senaste decennierna, drivet av både naturliga och antropogena faktorer, såsom förändringar i ekosystemens produktivitet, bränder och markanvändning. Markytans förändringar kan potentiellt påverka det lokala och regionala klimatet genom förändringar i processer som sker mellan jordytan och atmosfären. Markanvändningsförändringar förväntas fortsätta i framtiden och det är nödvändigt att öka förståelsen av interaktioner mellan jordytan och atmosfären, inklusive olika återkopplingsmekanismer, för att öka vår kunskap om framtida klimatförändringar. Styrkan i lokala interaktioner mellan landytan och atmosfären beror på olika landskaps förmåga att påverka utbytet av energi, vatten och växthusgaser. Även när dessa växelverkan sker lokalt kan det påverka klimatet regionalt och globalt genom cirkulationsförändringar som påverkar energi- och fukttransport, eller förändringar i molntäcket som i sin turpåverkar inkommande strålningen. Nedskalning av resultat från globala klimatmodeller med regionala jordningssystemmodeller (RESMs) förbättrar klimatsimuleringars rumsliga detaljer och återger mer korrekt klimatdynamik, speciellt i regioner med varierande topografi.

I denna avhandling använde jag en dynamisk nedskalningsmodell RCA-GUESS, en RESM som kopplar Rossby Centres regionala klimatmodell RCA4 till LPJ-GUESS, en ekosystemmodell som kombinerar en individbaserad representation av vegetationsstruktur och dynamik med processbaserad fysiologi och biogeokemi. Jag undersökte regionala markytefördändringar och relaterade interaktioner mellan jordytan och atmosfären över tre olika geografiska områden. Detta arbete bidrar till förståelsen av rollen av vegetationsdynamik och socioekonomiska faktorer − såsom markanvändning och bränder − i regional jordsystemsdynamik. I en markytestudie baserad på LPJ-GUESS simuleringar visar jag att framtida förändringar i brandregimen i Europa orsakad av klimat- och socioekonomiska förändringar är viktiga för att föruts äga framtida förändringar av markytan. Samspel mellan bränder och vegetation och socioekonomiska effekter identifierades som viktiga osäkerheter för framtida brandområden. Studien om land-atmosfär interaktioner baserade på RCA-GUESS simuleringar visar att det hydrologiska kretsloppet i tropikerna är känsligt för förändringar av marktäcket i halvtorra områden i Afrika, och att biofysiska kopplingar är viktiga genom deras förändrade regionala cirkulationsmönster. En studie baserad på analys av empiriska dataset och CMIP5 jordsystemsmodeller (ESMs) visar att bias hos simulerat klimat är den huvudsakliga orsaken till diskrepans mellan modeller och data. Modeller och data visar på ett liknande hydrologiskt förhållande som antyder att minskad nederbörd och ändrad markanvändning utgör de huvudsakliga hoten

för den framtida ecosystemet i Amazonas. En uppföljningsstudie baserad på RCA-GUESS simuleringar med realistiskt markanvändningsscenario visar de potentiella effekterna av markanvändning på de naturliga ekosystemens produktivitet i Amazonas som uppstår i och med påverkan på det lokala och regionala klimatet.

摘要

在过去的几十年里，观测数据和数值模拟均表明，自然和人为活动，包括生态系统生产力的变化，森林火灾和土地利用的变化，一直持续对全球地表产生重大影响。地表变化通过陆气相互作用可以对本地以及区域气候产生潜在的影响。持续的温室气体排放和社会经济变化也将继续驱动地表变化。这使得更深入了解陆气相互作用及其相关机制对于未来气候变化的影响显得尤为重要。陆气相互作用在不同情况下表现各异。本地相互作用的强度取决于不同地表类型对能量和物质交互能力的差异，包括潜热，显热，水和碳。本地的反馈作用也会影响区域甚至全球的气候，例如通过大气环流影响区域间能量和水汽的传输，或是通过影响云量从而影响入射太阳辐射。基于动力降尺度（Dynamical downscaling）和个体植被动态（Individual-based vegetation dynamics）的高分辨率区域模式地球模拟系统（RESM）较好的弥补了传统全球模式地球系统（ESMs）对于地形高度复杂或有显著季节性干旱区域的模拟的不足，能为区域陆气相互作用的研究提供更贴近现实的植被动态和生态物理反馈，更精确的区域气候动态，以及更丰富的区域空间信息。

本论文通过运用 RCA-GUESS，一个由瑞典 Rossby 中心的区域模式气候模型 RCA4，和综合了个体植被结构和动态，过程化植物生理和生物地球化学的生态系统模型 LPJ-GUESS 所组成的区域地球模拟系统，研究了区域性的自然和人为因素引起的植被变化和由此产生的陆气相互作用。研究区域包括欧洲，非洲和南美洲。基于离线模式下的 RCA-GUESS(LPJ-GUESS 和 RCA4 不耦合)的地表变化的研究表明，受未来气候和社会经济变化的驱动，未来欧洲的森林火情势对其地表变化有相当大的影响。其中，火情势和植被的交互作用和社会经济变化对所预测的火灾影响区域具有比较大的不确定性。基于耦合模式下的 RCA-GUESS 的陆气相互作用的研究表明，非洲半干旱地区的地表变化对非洲热带地区的水循环有重大的影响。其中，地表的生物物理反馈对区域性大气环流的变化起重要的作用。对观测和 CMIP5 ESMs 模拟结果的分析表明，气候模拟中的误差是模拟结果和观测数据的差异的主要原因。尽管如此，模型和观测均显示了一个重要的水文关系，并且表明了降雨的减少和土地利用构成了未来亚马逊森林的最大威胁。基于耦合模式下的 RCA-GUESS 的对亚马逊恢复力的研究表明，通过对本地和区域气候的影响，当代的土地利用可以对亚马逊的生态系统生产力产生潜在的正负并存的影响。

1.Introduction

1.1 Changes to global and regional land surfaces

The global land surfaces have been undergoing significant changes in the past few decades with accelerating global warming and intensifying regional extreme events (Stocker, 2013). Long-term satellite records have revealed significant vegetation shifts globally, in particular for the transition regions such as savanna and the northern high-latitude areas (de Jong et al., 2013). The so-called Anthropocene has arrived, an era which encompasses increasing and widespread anthropogenic influences including long-term and large-scale land use changes (Crutzen, 2002), which have led to decayed ecosystem functioning and biodiversity loss (Davidson et al., 2012) that are expected to persist for many decades to come (Hurtt et al., 2011). Recent estimates revealed that 42–68% of the global land surface had been impacted by land-use activities over the period 1700-2000, including land conversion for crops and pasture, and wood harvest (Hurtt et al., 2006). Fires associated with climate change and human activities have been shaping the global land surface (Bowman et al., 2009) with on average 348 Mha burned area per year (Giglio et al., 2013), but with a strong regional variation. Fires are expected to continue imposing profound impacts under future climate change (Knorr et al., 2016).

Causes and consequences of land surface changes differ regionally. For Mediterranean Europe, wildfire causes large ecosystem and socioeconomic losses, and extreme fire events alter the landscape considerably by producing large fragmentations in forested area (San-Miguel-Ayanz et al., 2013). For the Amazon, agricultural expansion has led to 17% of forest lost (Knox et al., 2011), a figure that could increase to 40% by 2050 if the current deforestation trends persist (Soares-Filho et al., 2006). For Africa, more than 50% of the land surface has experienced conspicuous greening and browning (positive and negative trends of vegetation productivity, respectively), with the most marked changes over savannas (de Jong et al., 2013).

These land surface changes were driven by recent changes in climatic conditions and by impacts from human activities, and they have the potential to influence local and regional future climate through land-atmosphere interactions governed by various feedback mechanisms (Bonan, 2008b, Levis, 2010). The sign and strength of such feedbacks mainly depend on the capabilities of different land cover types to control surface energy and mass exchanges, including energy, water and carbon. The feedbacks also include locally-forced remote influences on

regional climates, for example locally-derived circulation changes can influence regional energy and moisture transport, and affect regional cloud cover and incoming solar radiation. Land surface-related feedbacks can be categorized as biogeophysical - processes that are based mostly on physical land surface properties, such as albedo and surface roughness - or biogeochemical (Levis, 2010), and both are closely associated with terrestrial ecosystems in terms of vegetation composition, structure and functioning. For the study of vegetation feedbacks in regional Earth system dynamics, I will mainly focus on biogeophysical feedbacks in the following sections.

1.2 Vegetation dynamics

Carbon is an important element for structural compounds of vegetation. The structure and functioning of vegetation are the results of physiological processes, including photosynthesis, respiration and tissue turnover that govern the vegetation carbon balance (Chapin III et al., 2011). Vegetation growth, termed as net primary productivity (NPP), is expressed as the balance between photosynthesis and autotrophic respiration. Photosynthesis and autotrophic respiration are constrained by stomatal conductance, temperature and water availability. Vegetation perishes represented as carbon lost due to mortality and disturbance (Chapin III et al., 2011). These processes differ due to regional variation in climate and vegetation adaptation strategies controlling the variation of NPP that reflects temporal and spatial changes in vegetation structure.

For the temperate regions, the dominant deciduous forest exhibits a larger seasonal variation in structure than the cold coniferous forest and tropical evergreen forest. The former are more sensitive to changes in temperature that controls the growing season than the latter, although NPP within the growing season is similar between these biomes (Kerkhoff et al., 2005). Seasonality for tropical moist forest is less well defined because of the relatively long rainy season that leads to low variation in soil moisture throughout the year. Vegetation adaption strategy also plays an important role in controlling vegetation structure. Generally, the NPP that is allocated to sapwood during a previous growing season provides the initial support for vegetation growth for the current year. NPP allocation to biomass compartments (leaves, fine roots and sapwood) is subject to allometric constraints, e.g. foliage to root ratio, under certain resource limitations, e.g. water and nitrogen availability, and these constraints differ between species (Kozlowski and Pallardy, 2002). Given similar resource conditions, deciduous plants may allocate NPP to foliage earlier than would evergreens during the growing season (Kummerow et al., 1983). The resultant leaf area depends on the amount of allocated biomass to

foliage, and it also depends on species-specific leaf traits, e.g. specific leaf area (SLA). Leaf longevity is controlled by phenology strategy. Deciduous species shed their leaves under unfavorable growing conditions to avoid carbon loss from maintenance for the existing leaf tissues, while evergreen species prefer to keep their leaves on for a longer period to avoid yearly carbon loss from leaf replacement, but this comes at the cost of enhanced maintenance, including carbon lost from respiration and higher risk from disturbances (Chabot and Hicks, 1982, Chapin III et al., 2011).

On decadal or century scales, elevated atmospheric CO_2 concentrations may impose profound influences on vegetation that differs from present-day processes under lower CO_2 concentration. Stomatal conductance controls the balance between photosynthesis and transpiration, expressed as photosynthetic water use efficiency (WUE). Elevated CO_2 optimizes the effects of CO_2 supply on photosynthesis and potentially increases WUE. This effect is most pronounced in C_3 woody plants (Ainsworth and Long, 2005) and can be important to vegetation dynamics under future climate change. It implies that C_3 plants may be more resistant to future drought than C_4 plants, and competitive balances between C_3 and C_4 plants may be altered, especially for the tropics where C_4 and C_3 species usually co-exist.

Vegetation is not only controlled by physiological processes, but it is also significantly influenced by disturbances. One of the most important disturbances is fire, which influences vegetation dynamics locally and globally (Bowman et al., 2009). Fire is triggered by climatic extremes or/and anthropogenic ignitions, and grounded by flammable fuels supplied from vegetation. It alters vegetation structure and ecosystem functioning by biomass burning and post-fire mortality (Randerson et al., 2006), resulting in a balancing feedback loop between fire and vegetation, whereby fire reduces fuel load and constrains further burning. It is suggested that fire is important to the bistable state of certain ecosystems, and that the present-day savanna is the result of a long-term fire-vegetation equilibrium (Moncrieff et al., 2014, Favier et al., 2012). Socioeconomic drivers also play a significant role here. Contemporary fire patterns have been strongly associated with human activities (Marlon et al., 2008), represented as, e.g., forest clearing fire and agricultural burning. The influences of socioeconomic drivers on fire in future, however, could mainly be represented as a fire-suppression effect (Knorr et al., 2014, Knorr et al., 2016). In the following section I will introduce the role of land use changes, which is one of the major socioeconomic drivers for land surface changes.

1.3 Land use and land cover changes

At present, large-scale land use changes have extended to most parts of the world except cold high-latitude regions such as Antarctica and Siberia, and tropical rainforest regions such as parts of the Amazon and Congo basins. It is estimated that the present-day land use area covers up to one third of the global land area, with around 11% for cropland and 25% for pasture (Pielke et al., 2011). Land use is strongly driven by socioeconomic development in terms of population growth and changes in diets (Alexander et al., 2015, Smil, 2002), changes in agriculture practice (Kaplan et al., 2010) and energy security strategies (Fairley, 2011). It is believed that future changes in land use will continue to be driven by socioeconomic changes, e.g., the expected increase in global population by at least 30% of present-day level (Jiang, 2014) and the continuous transition toward a high-sugar and high-protein diet (Tilman and Clark, 2014). Land use changes are also affected by global geopolitical agreements to control greenhouse gas emissions to achieve mitigation targets (Stocker, 2013).

Land use area is generally characterized as low-vegetated land with physical properties that are distinctly different from forest. E.g., when rainforest is converted into crop land or pasture, increases in albedo, reduced surface roughness and low-level vertical mixing, and reduced evaporative efficiency could occur (Bonan, 2008b). In the following section, I will discuss the land-atmosphere interaction in more detail.

1.4 Land-atmosphere interactions

1.4.1 Vegetation feedbacks

Ecosystems with diverse structure and functioning are affected by biotic and abiotic drivers, their different physical features influencing land surface processes through vegetation feedbacks (figure 1). The largest contrasting differences can be seen when forests are compared with open land. Forests tend to absorb a higher proportion of the incoming shortwave radiation than pasture due to their lower albedo (Jin et al., 2002). Forests with a rougher surface generally have lower aerodynamic resistance which facilitates vertical mixing and thus energy and water exchanges (Bonan, 2008a). Moreover, a forest canopy provides larger storage for intercepted rainfall, thus imposing stronger influences on evaporation, surface temperature and runoff than herbaceous vegetation (Noilhan and Planton, 1989). Forests with larger rooting depths are able to access soil water from deeper

soil layers and are thus less influenced by seasonal drought (Gash and Nobre, 1997).

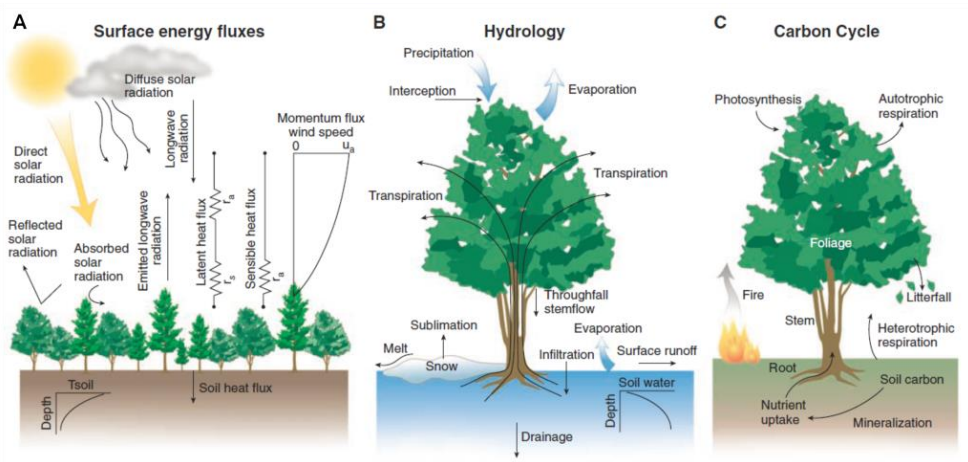

Figure 1.
Vegetation-climate feedbacks influence land surface processes, including surface energy fluxes (a), the hydrological cycle (b) and the terrestrial carbon cycle (c). From (Bonan, 2008b), reprinted with permission from AAAS.

There are also differences between woody biomes, although the contrasts are not as large as the woody-herbaceous contrast. Tropical wet forests (0.1-0.3) generally have a lower Bowen ratio than temperate forest (0.4-0.8) and boreal forest (0.5-1.5) (Jarvis, 1976, Eugster et al., 2000). Tropical forests have 2-10 times larger rooting depth than temperate and boreal forests (Canadell et al., 1996). These differences imply that changes in land-atmosphere interactions may also occur with changes in ecosystem composition, but the effects should be smaller due to smaller physical contrast compared to the effects of shift from high to low vegetated cover. Overall, land surface changes, driven by both natural and anthropogenic perturbations, could influence land surface feedbacks to climate.

1.4.2 Regional differences and future climate change

Previous modelling studies have indicated that deforestation generally imposes a warming effect over tropical regions, and a cooling effect over high-latitude regions (Zhang et al., 1996, Bala et al., 2007). These studies stress different mechanisms for these regions: evaporative cooling for tropical forest may be stronger than its albedo-induced warming, whereas for high-latitude biomes albedo-induced warming is more dominant.

In addition, land surface changes over the tropics may impact the meso- or large-scale circulation system when changes to latent heat fluxes affect vertical temperature profile, boundary layer entropy and atmospheric flow convergence in the boundary layer (Eltahir, 1996, Werth and Avissar, 2002). Such dynamics are hypothesized to be weaker for high-latitude regions, where the role of the hydrological cycle is not as important.

Future climate change assessments could become more robust with better representation of land surface changes including the representation of ecosystem heterogeneity. Under future climate change, high-latitude areas are likely to experience larger increase in temperature and precipitation than other parts of the world (Stocker, 2013). High-latitude ecosystems are expected to experience a longer growing season and systematic shifts in vegetation resulting in biogeophysical feedbacks on the local climate system (Pearson et al., 2013). Although the confidence in projections of future changes in precipitation over the tropics and subtropics is lower than for high-latitude areas (Stocker, 2013), globally, ecosystems at the fringe of tropical forests, which are usually constrained by precipitation, are nevertheless likely to encroach pole-ward by enhanced WUE under conditions of elevated CO_2 concentration alone (Long, 1991, Hickler et al., 2008). This can lead to significant local and mesoscale biogeophysical feedbacks on the tropical climate (Brovkin et al., 2013, Boysen et al., 2014). In view of the importance of biogeophysical feedbacks induced by vegetation dynamics, it has been suggested that consideration of land surface changes with vegetation dynamics is required to assess the long-term response of the carbon cycle (Meinshausen et al., 2011).

1.4.3 Uncertainties in the assessment of land-atmosphere interactions

Research methods for assessing land-atmosphere interactions vary, encompassing field measurements, satellite-based analysis, and studies with Earth System Models (ESM). Thanks to technology development, instruments and facilities used for Earth science research have greatly improved with regard to the temporal and spatial resolutions and stability in the last couple of decades. However, there is still uncertainty in land-atmosphere interaction studies. One typical example is the assessment of the impacts of tropical deforestation on the hydrological cycle, where opposite conclusions are not difficult to find from satellite-based analysis and ESM modelling studies. Satellite-based analysis with a coarse sampling grid ($2.5^\circ \times 2.5^\circ$) found lower annual precipitation over the deforested area than the forest for the Amazon arc of deforestation region (Durieux et al., 2003), which agreed with the deforestation study with ESM simulations (Costa and Pires, 2010). But they were in contrast with the satellite-based analysis with finer sampling

resolution (0.5˚ × 0.5˚) (Negri et al., 2004) and the deforestation study with RESM simulations (Correia et al., 2008) who found pronounced increase in precipitation.

Previous ESM studies that have examined the impacts of global land use and land cover changes (LULCC) suggest a weak negative radiative forcing with a global average of -0.15 W m^{-2} in 2011 relative to 1750 due to albedo changes with medium level of confidence (Stocker, 2013). ESM studies for the impacts of Amazonian deforestation with realistic deforestation patterns that reflect historical trends tend to show small magnitude changes in temperature and rainfall, but exhibit contrasting directions of change in different parts of the deforested area or among different models and scenarios (Pitman et al., 2009, Findell et al., 2007). This uncertainty comes at least in part from differences in the model values used for the albedo of natural and managed surface, the ability of the land surface scheme (LSS) to represent local land-atmosphere interaction (e.g. different model performances are found when using tiled approaches and parameter averaging approaches to represent the surface energy balance on different scales (Koster and Suarez, 1992)), and possible LULCC-induced changes in regional circulation affecting the local climate system (Findell et al., 2009, Werth and Avissar, 2002). In view of the possible influences of model complexity on model uncertainties, a better understanding of land-atmosphere interactions may require disentangling the effects of local climate drivers from regional or global drivers (Lawrence and Vandecar, 2015). In the following section I will introduce the added value of regional ESMs when compared with traditional ESMs, and how they are applied for studies of regional land-atmosphere interactions.

1.5 Regional Earth system models − tools for investigating land-atmosphere interactions

1.5.1 Researching regional-scale climates

Global climate models, including global ESMs, are the established prominent research tools for climate projections. However, their resolutions are still largely too coarse for resolving important details of regional-scale climate (Myhre et al., 2013). Downscaling with regional ESMs (RESMs) adds value to the global climate model simulations for the regions with highly variable topography, providing richer spatial details (Rummukainen, 2010, Rummukainen, 2016). They capture regional climate dynamics in particular for topography-influenced phenomena (Feser et al., 2011), such as Alpine temperature (e.g. Prömmel et al., 2010) and coastal climatology (e.g. Winterfeldt et al., 2011). They also show

advantages in simulating extreme events, such as extreme precipitation (e.g. Kanada et al., 2008), extreme wind speed (e.g. Kunz et al., 2010), and convective precipitation (Rauscher et al., 2010). In some cases, the downscaling approach with RESMs even outperforms the reanalysis product when the RESM is driven by the boundary condition from the reanalysis. For example, running 10 regional circulation models (RCMs) over Africa using a common experiment protocol with the boundary conditions from ERA-Interim, Nikulin et al. (2012) demonstrated a better simulated precipitation than the ERA-Interim reanalysis itself, based on the evaluation against different observational datasets. This may be because the downscaling can resolve the precipitation process more explicitly and it becomes less dependent on parameterizations (Rauscher et al., 2010). The improved simulation of smaller-scale processes can in turn improve simulation of larger scale phenomena (Lorenz and Jacob, 2005, Inatsu and Kimoto, 2009), such as large-scale monsoon precipitation patterns (Gao et al., 2012) and tropical circulation patterns (Lorenz and Jacob, 2005).

1.5.2 The development of coupling vegetation dynamics in the RESMs

Akin to many general circulation models (GCMs), especially until very recently, RCMs have focused on the atmosphere and land surface without dynamic vegetation. Vegetation dynamics are, however, an important feature in the climate system. Their incorporation into ESMs began in the 1990s and this had become more common at the time of the IPCC's 5th Assessment Report (AR5, Flato et al., 2013). In contrast, the incorporation of vegetation dynamics into RCMs is still relatively uncommon. Still today, only a few RCMs are coupled with dynamic vegetation models (Table 1), and can be called a RESM.

The implemented coupled vegetation dynamics in RESMs mainly focus on the impacts from biophysical changes, which can influence the climate through changes in vegetation structure. Vegetation dynamics also feed back to the climate system via changes in sub-grid fractions of averaging PFTs, i.e. vegetation composition. The averaging values can be derived from either "area-based" models such as CLM-DGVM (Levis et al., 2004) and LPJ-DGVM (Sitch et al., 2003), or "gap"-like models such as LPJ-GUESS (Smith et al., 2001). A previous comparison of LPJ-DGVM and LPJ-GUESS (Smith et al., 2001) suggested that vegetation dynamics are better represented in LPJ-GUESS than LPJ-DGVM due to its mechanistic and independent treatment of resource competition (light, water, and space), and also due to its individual-based representation of vegetation, which is able to capture differences in size and form among individuals.

From a technical point of view, the component of vegetation dynamics that is incorporated into the LSS of a climate model, acts either as an inherent part of the LSS; an "inclusion" approach (e.g. Chen and Xie, 2012), or as an external sub-component using some coupling technique in an asynchronous or synchronous way; a "portable" approach (e.g. Göttel et al., 2008). The inclusion approach has the advantage of conceptual consistency, but the vegetation and physical components tend to be tightly joined under a common framework and the interfaces between them are more difficult to define, they are thus less flexible for future model development. The portable approach has a clear definition between sub-models, thus providing an easy cooperation between Earth System modelling communities, but the main challenge lies in how to harmonize the possible conceptual inconsistency for some key processes between sub-models. Such key processes can be, for example, the hydrological cycle or the thermal dynamics in the soil scheme, which may exist in each sub-model.

Although model development in some cases has to compromise model complexity due to computational constraints, there is a trend to increasingly include more sophisticated processes with richer details. Increasing model complexity, however, may also produce additional uncertainty in some situations. Pitman et al. (2009) found that the inclusion of land cover change in ESMs introduced additional spread in regional climate projections. Further to the discussion about model uncertainties aforementioned, this can also arise from the difference in sensitivity of the models' evapotranspiration (ET) and albedo responses to land cover changes (Boisier et al., 2012) that had significant impacts on temperature and precipitation (Pitman et al., 2012). In general, increased complexity increases the degrees of freedom of the model and may give rise to additional uncertainties. Indeed, the land surface model behaviour can depend on how vegetation types are parameterized, how the LSS tiles represent the surface and how strongly the surface is coupled to the atmosphere (Seneviratne et al., 2006, Pitman et al., 2009).

Table 1.
Previous studies of vegetation-climate interaction using RESMs with vegetation dynamics.

Model Name	(1) DGVMs Coupled (2) Main references	Feedback variables	Coupling interval	Study region	Main findings
RAMS	(1) CENTURY (2) (Lu et al., 2001)	LAI	weekly	Central United States	Seasonal vegetation phenological variation strongly influences regional climate patterns through its control over land surface water and energy exchange.
RCA-GUESS	(1) LPJ-GUESS (2) (Smith et al., 2011)	LAI, forest fraction	fully coupled, daily	Europe	Feedback effects are rather modest: feedbacks contribute 0.2-1˚C increase for southern Europe and 0.2-0.5˚C decrease for northern and central Europe.
REMO	(1) LPJ-GUESS (2) (Göttel et al., 2008)	LAI, forest fraction	asynchrono-usly	Barents Sea Region	Strong warming effect in summer and cooling effect in winter in Siberia.
	(1) iMOVE (vegetation representation originates from JSBACH) (2) (Wilhelm et al., 2014)	LAI	fully coupled	Europe	Vegetation dynamics imposes important impacts on near surface cliamte.Soil hydrology is important in controling vegetation growth.
RegCM3	(1) CLM-DGVM (2) (Alo and Wang, 2010)	LAI, vegetation type	asynchrono-usly , yearly	West Africa	Precipitation increase by 23% over the Sahel in summer compared 5% decrease without vegetation feedback.
	(1) CERES (land-surface scheme derived from BATS) (2) (Chen and Xie, 2012)	LAI, stem area index, root fraction	fully coupled, daily	East Asian monsoon area	Reduced RMSE of the simulated precipitation by 2.2-10.7% over north China.
WRF3	(1) CLM3.5 (2) (Lu and Kueppers, 2012)	LAI, stem area index, PFTs fraction	fully coupled	United States	Strong soil moisture-precipitation feedback in Midwest irrigated area.

2.Aims and objectives

In view of the importance of land-atmosphere interactions to regional and global climate, and the critical role of regional climate dynamics to global climate change, greater understanding of the underlying mechanisms of land-atmosphere interactions at a regional scale, including regional biophysical feedbacks and the impacts of socioeconomic changes on regional land cover is required. In this thesis, I investigated:

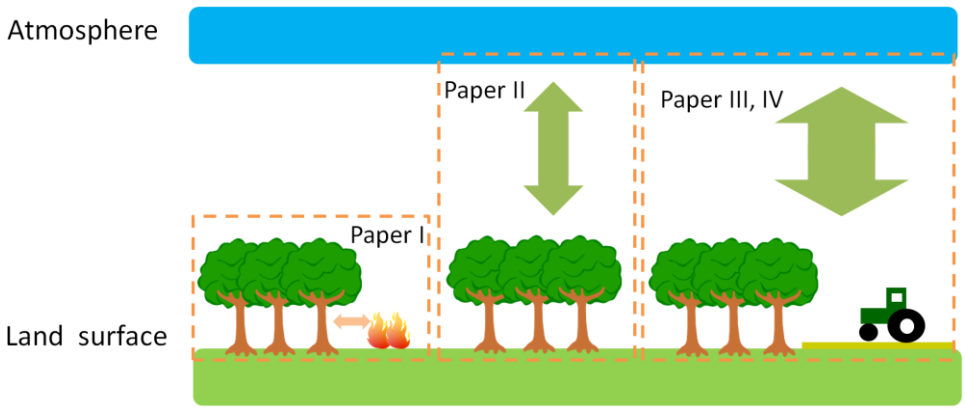

Figure 2.
Overview of this thesis.

1. The roles of socioeconomic and climate change in affecting the land surface through changes in the fire regime. In my first study, I investigated how wildfire affected terrestrial ecosystems under future climate change, when considering changes in human population density as well as the elevated CO_2 concentration. Europe was selected as a case study region (Paper I, figure 2).
2. The role of vegetation dynamics in affecting regional climate through biophysical feedbacks. In this study, Africa was chosen as a case study region (Paper II, figure 2).
3. The roles of vegetation dynamics and LULCC in affecting regional land-atmosphere interaction and their influences on regional climate and terrestrial ecosystems. In these studies, the underlying mechanisms for the present-day and the future were investigated. South America was chosen as a case study region (Paper III, IV, figure 2).

3. Methods

I applied a dynamical downscaling approach (figure 3) by employing RCA-GUESS (Smith et al., 2011), a regional Earth system model that couples the Rossby Centre regional climate model RCA4 (Kjellström et al., 2005, Samuelsson et al., 2011) to LPJ-GUESS, an individual-based ecosystem model that combines an individual-based representation of vegetation structure and dynamics with process-based physiology and biogeochemistry (Smith et al., 2001, Smith et al., 2014). A study with offline LPJ-GUESS was also included.

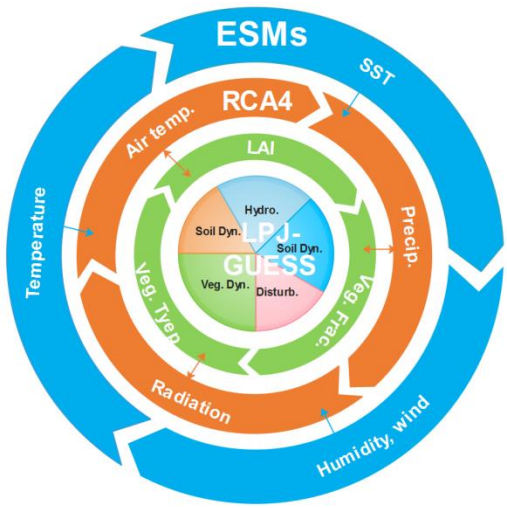

Figure 3.
Schematic diagram for the dynamic downscaling/regional Earth system modelling framework.

3.1 LPJ-GUESS

The dynamic ecosystem model LPJ-GUESS, which also constitutes the vegetation dynamics component of RCA-GUESS, employs a plant individual and patch-based representation of the vegetated landscape, optimized for studies at regional and global scale. Heterogeneities of vegetation structure and their effects on ecosystem function such as carbon and water vapour exchange with the atmosphere are represented dynamically, affected by allometric growth of age-size classes of woody plant individuals, along with a grass understorey, and their interactions in competition for limited light and soil resources. Plant functional types (PFTs) encapsulate the differential functional responses of potentially-occurring species in terms of growth form, bioclimatic distribution, phenology,

physiology and life-history characteristics. Multiple patches in each vegetated tile account for the effects of stochastic disturbances, establishment and mortality on local stand history (Smith et al., 2001). This explicit, dynamic representation of vertical structure and landscape heterogeneity of vegetation has been shown to result in realistic simulated vegetation dynamics in numerous studies using the offline LPJ-GUESS model (Piao et al., 2013, Wårlind et al., 2014, Smith et al., 2014, Smith et al., 2001).

To address changes in fire regimes in response to future climate change, changes in atmospheric CO_2 concentration and demographics (Paper I), I employed a semi-empirical fire model (Knorr et al., 2015), which predicts annual burned area on the basis of biome type and photosynthetically active radiation absorbed by vegetation (determined from vegetation characteristics simulated by LPJ-GUESS), climatic fire danger (defined as the probability of burning from climate forcing), and human population density (provided as external forcing).

3.2 RCA-GUESS

The RCA4-based physical component of RCA-GUESS incorporates advanced regional surface heterogeneity, such as complex topography and multi-level representations of forests and lakes, which are important for the development of weather events from the local to mesoscale (Samuelsson et al., 2011). RCA4 has been applied different regions on the globe, including the Arctic (e.g. Döscher et al., 2010), Europe (e.g. Kjellström et al., 2011), Africa (e.g. Nikulin et al., 2012) and South America (e.g. Sörensson and Menéndez, 2011).

The LSS in RCA4 (Samuelsson et al., 2006) adopts a tile approach and characterizes the land surface with open land and forest tiles with separate energy balances. The open land tile is divided into fractions for (herbaceous) vegetation and bare soil. The forest tile is vertically divided into three sub-levels (canopy, forest floor and soil). Surface properties such as surface temperature, humidity and turbulent heat fluxes (latent and sensible heat fluxes) for different tiles in a grid box are weighted to provide grid-averaged values. A detailed description is given by Samuelsson et al. (2006).

The simulated vegetation structure by LPJ-GUESS affects the land surface properties (albedo and roughness length, as well as the water vapour exchanges with the atmosphere) by returning updated forest and open land tile fractions (yearly) and leaf area index (LAI, daily) for each of the tiles to the LSS in RCA4 (figure 4).

For the land-atmosphere interaction study (Paper IV) in this thesis, different treatments of anthropogenic land use were applied. In RCA-GUESS, land surface

information is provided by LPJ-GUESS. For the potential natural vegetation (PNV) mode (used in Paper II), LPJ-GUESS provides simulated annual potential forest and open land fractions annually for the LSS in RCA4. For the static land use (SLU) mode, land use fractions for forest and open land are prescribed from external datasets, such as ECOCLIMAP. The open land fraction is allowed to adjust when forest retreat occurs in response to unfavourable climate forcing. In this case, the original forest fraction will be converted into the open land fraction and the remaining forest LAI is counted toward the LAI of the open land tile (Smith et al., 2011). Based on the SLU mode, a dynamic land use (DLU) mode was developed for study IV by replacing the static land use information with annually varying land use information. In this case, pasture and crop fractions are grouped to determine the fraction of open land. Similar to the SLU mode, the land use fraction is dynamically adjusted according to the simulated state for the forest tile and is always larger than the initial land use fraction.

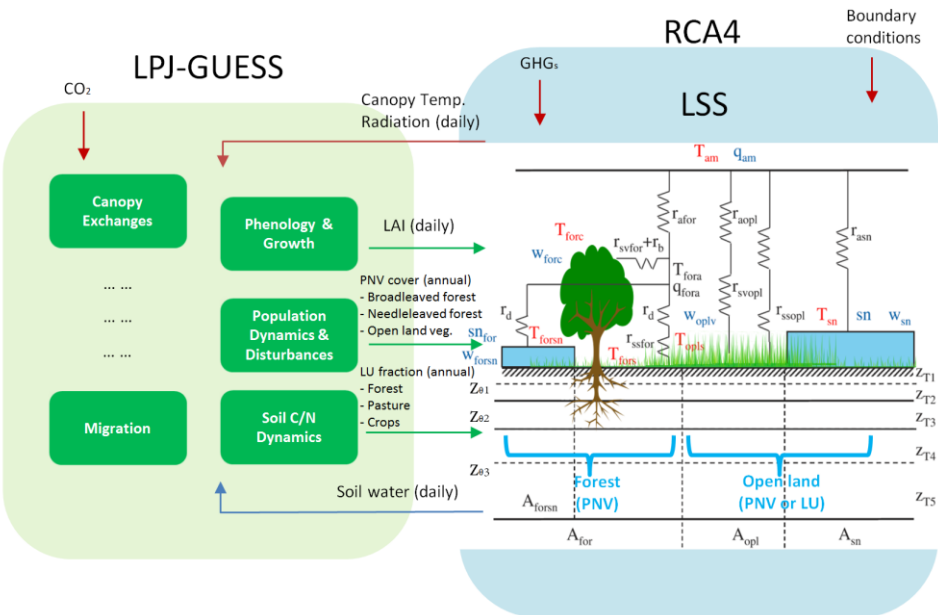

Figure 4.
Schematic diagram of the coupling scheme between LPJ-GUESS and RCA4. Figure of LSS is adapted from Samuelsson et al. (2006).

Biophysical feedbacks have previously been studied in applications of RCA-GUESS to Europe (Wramneby et al., 2010, Smith et al., 2011) and the Arctic (Zhang et al., 2014). A more detailed description of the model is given by Smith et al. (2011).

3.3 Experiments and data

The studies in this thesis were based on domains for Europe (Paper I), Africa (Paper II) and South America (Paper III & IV; figure 5). Simulations with the (offline) model LPJ-GUESS and the coupled model RCA-GUESS (Table 1) require different experimental configurations for different simulation domains. For the offline simulations (Paper I), the coordinates of the simulation domain need to be regridded to Gaussian grid with $0.5° \times 0.5°$ horizontal resolution to align with the coordinates of the forcing data used in LPJ-GUESS. For the online studies (Paper II & IV), the RCA's rotated pole coordinate system with $0.44° \times 0.44°$ horizontal resolution is used for the domains of interest. Further details for the domain setting for the online RCA-GUESS studies are available on the project website for the Coordinated Regional Climate Downscaling Experiment (CORDEX, www.cordex.org/).

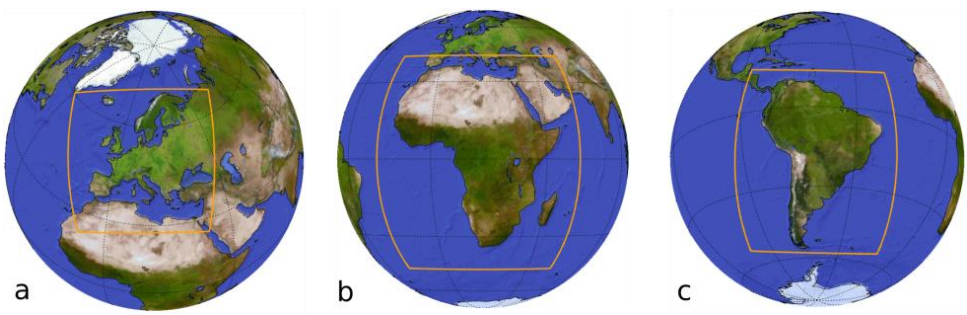

Figure 5.
Study domains in this thesis. (a), European domain for the offline study in Paper I, but a region between 15˚W and 38˚E, and 35˚S and 72˚N is used in order to cover all the European countries. (b), African domain for the online study in Paper II, and (c), South American domain for the analysis study in Papers III and the online study in Paper IV (adapted from www.cordex.org).

Simulations with LPJ-GUESS require climate data (temperature, precipitation, radiation) as forcing. The forcing dataset for the offline simulations can be taken from gridded observations, or from climate model simulations. For Paper I, I applied climate data from several ESMs under different climate scenarios (Table 2), and used statistical downscaling techniques when the resolution of the forcing data is coarser than that of interest. For example, in this study, ESM climate forcings were interpolated to a $0.5° \times 0.5°$ spatial grid resolution and bias-corrected against datasets from the Climatic Research Unit (CRU) following Ahlström et al. (2012): monthly mean temperature and shortwave radiation were linearly interpolated to daily values, and daily precipitation was simulated by a weather generator based on monthly fraction of rain days. For the coupled simulations, the physical component RCA was forced with global climate model

data as initial and boundary conditions, and the coupled dynamic ecosystem component operated on the same spatial domain as RCA (Papers II & IV). In this case, the relationships between different climate quantities are more physically consistent between the two components, providing a more realistic basis for the studies of land-surface interactions.

Observation data sets for the model evaluation encompassed field measurement observation (e.g. European fire database), satellite-based (e.g. GFED3.1) and gauge-based (e.g. CRU) observations as well as reanalysis datasets (e.g. ERA-Interim). They are summarized in Table 2.

Table 2.
Experiment setup and validation data used in this thesis.

Paper	Experiments/ Analysis	Period	Model	Forcing data (scenarios)/Main analysis data	Evaluation data (variables used)
I	Fire sensitivity	1961-2100	LPJ-GUESS	CRU TS3.1[©], MPI-ESM-LR[β] (RCP2.6 & RCP8.5), IPSL-CM5A-MR[β] (RCP2.6 & RCP8.5), HadGEM2-ES[β] (RCP2.6 & RCP8.5), CCSM4[β] (RCP2.6 & RCP8.5), SSPs[k] (SSP1 & SSP5)	EFFIS[a], GFED3.1[b], GFED4.1s[c] (Burned area for all datasets)
II	Vegetation feedback	1961-2100	RCA-GUESS	ERA-Interim[ε] CanESM2 [β] (RCP8.5)	CRU TS 3.23[d] (Temp. & Precip.), GPCP[e] (Precip.), LAI3g[f] (LAI), HadISSTv1.1[g] (SSTs) ERA-Interim[ε] (specific humidity & wind speed at 850hPa)
III	Hydrological relationship	1982-2100	ESMs	CanESM2[β](RCP8.5) CCSM4[β](RCP8.5) CESM1[β](RCP8.5) GFDL-ESM2M[β](RCP8.5) HadGEM2-ES[β](RCP8.5) IPSL-CM5A-MR[β] (RCP8.5) MIROC-ESM[β](RCP8.5) MIROC-ESM-CHEM[β](RCP8.5) MPI-ESM-LR[β](RCP8.5)	AGB dataset[h] (AGB) Upscaled FLUXNET dataset[i](GPP, ET) MODIS ET[j](ET)
IV	LU impacts on vegetation dynamics	1980-2005	RCA-GUESS	ERA-Interim[ε]	CRU TS3.21[d1], CRUNCEP v5[d2], Princeton V2[d3], WFDEI GPCC[d4], (Temp. & Precip for all above.), LAI3g[f] (LAI), AGB dataset[h] (AGB)

Note:
[©,d,d1]: The Climatic Research Unit Timeseries (CRU) global historical datasets (Harris et al., 2014), available at http://www.cru.uea.ac.uk/data
[β]: ESMs outputs from Coupled Model Intercomparison Project Phase 5 (CMIP5).
[ε]: The ERA-Interim datasets (Berrisford et al., 2009), available at http://apps.ecmwf.int/datasets/
[a]: Monthly burned area data from the European Fire Database (Camia et al., 2010) of the European Forest Fire Information System (EFFIS; http://effis.jrc.ec.europa.eu)
[b]: The Global Fire Emission Database version 3.1 (Giglio et al., 2010).
[c]: The Global Fire Emission Database version 4.1 with small fires (Randerson et al., 2012).
[d2]: The North American Carbon Program Multi-scale Synthesis and Terrestrial Model Intercomparison Project (Wei et al., 2014).
[d3]: 50-Year High-Resolution Global Dataset of Meteorological Forcings for Land Surface Modeling (Sheffield et al., 2006).
[d4]: The Water and Global Change (WATCH) Forcing Data (Weedon et al., 2011).
[e]:The GPCP datasets (Huffman et al., 2001), available at http://precip.gsfc.nasa.gov/gpcp_daily_comb.html
[f]:The GIMMS-AVHRR and MODIS-based LAI3g product (Zhu et al., 2013), available at http://cliveg.bu.edu/modismisr/lai3g-fpar3g.html
[g]:The HadISSTv1.1 datasets (Rayner et al., 2003), available at http://www.metoffice.gov.uk/hadobs/hadisst/
[h]:Above ground biomass (AGB), from the global terrestrial biomass datasets (Liu et al., 2015)
[i]: Upscaled eddy-flux estimates (Jung et al., 2011).
[j]: MODIS global evapotranspiration products (Mu et al., 2011).
[k]:Shared Socioeconomic Pathways dataset, available at https://tntcat.iiasa.ac.at/SspDb/.

4.Results and discussion

4.1 Fire-vegetation interaction under socioeconomic changes for Europe (Paper I)

This study evaluated the impacts of wildfire, which is one of the most important drivers of land cover changes. Wildfire influences land surface albedo, the terrestrial carbon cycle and vegetation dynamics at regional and global scales (Bowman et al., 2009). Global environmental change and human activity influence wildfires worldwide, but the relative importance of individual factors varies regionally, and their interplay can be difficult to disentangle. In this study, I evaluated projected future changes in burned area at the European scale, and investigated uncertainties in the relative importance of the determining factors. I simulated future burned area with LPJ-GUESS-SIMFIRE, a patch-dynamic global vegetation model with a semi-empirical fire model, and LPJmL-SPITFIRE, a dynamic global vegetation model with a process-based fire model. Applying a range of future projections that combine different scenarios for climate change, enhanced CO_2 concentrations and population growth, I investigated the individual and combined effects of these drivers on the total area and regions affected by fire in the 21st century (figure 6).

I found that simulated wildfire over Europe from the two models differed notably with respect to the dominating drivers and underlying processes. Fire-vegetation interactions and socioeconomic effects emerged as important uncertainties for future burned area in some European regions. Predictions of burned area in eastern Europe increased in both models, pointing at an emerging new fire-prone region that should gain further attention for future fire management. Findings in this study also implied that future land-atmosphere interaction studies should also consider the uncertainty in simulating wildfire and its influences on land surface properties, such as burned area, albedo, and fire-vegetation interaction, as well as its relationship with land surface changes induced by other anthropogenic activities, such as land use and land cover changes (LULCC).

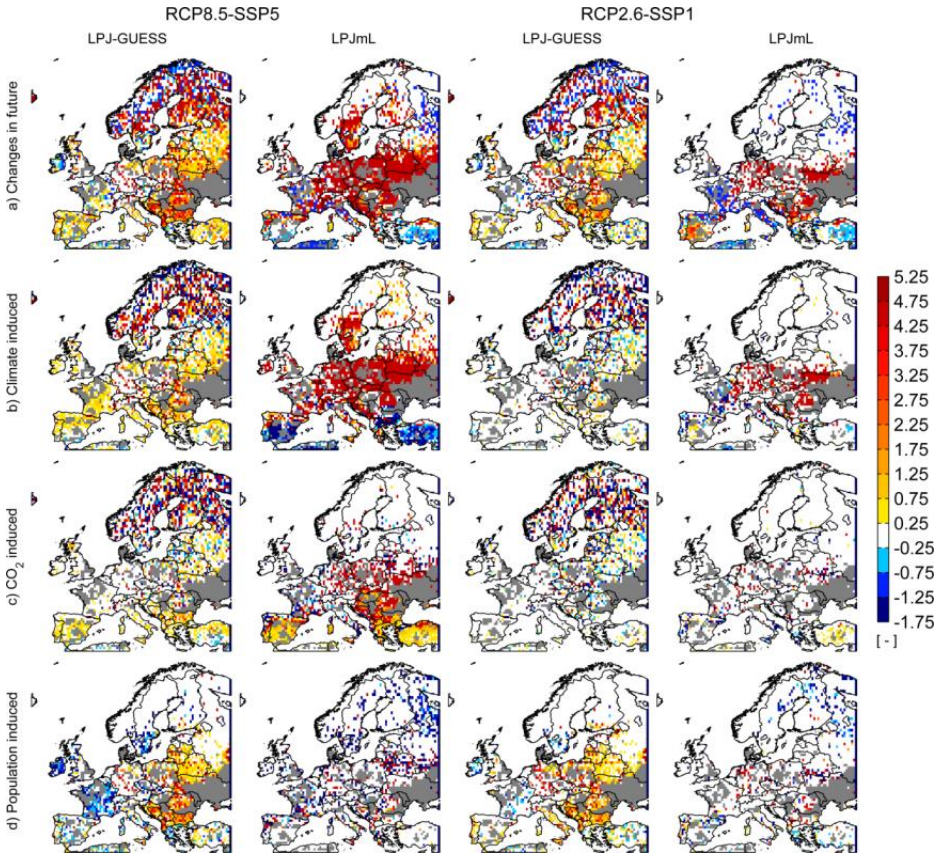

Figure 6.
Changes in mean annual burned fraction (BF) related to present-day in MPI-ESM-LR simulations with LPJ-GUESS and LPJmL. a): relative changes between future (2081-2100) and present-day (1981-2000) in the full-effect experiments ($BF_{future}/BF_{present\text{-}day}$ - 1); b) to d): Relative factorial effect for annual burned area fraction in future. Only significant changes (Mann-Whitney U-test, $p<0.05$) are presented. Areas with no change or non-significant change are in white. Areas with greater than 50% agricultural land were excluded (grey).

4.2 Land-atmosphere interaction with vegetation feedback for Africa (Paper II)

This paper evaluated the possible impacts of land surface changes resulting from natural vegetation dynamics on regional climate, and investigates their implications for future projected climate. Africa was chosen as the study domain because significant changes in vegetation dynamics are likely to happen over semi-arid areas in future, such as the fringe of rainforest or savanna area, which has been found to be sensitive to present-day climate variations in previous

modelling (Ahlström et al., 2015) and tree-ring (Touchan et al., 2011) studies. Satellite-based studies also showed that Africa has been undergoing significant changes in climate patterns and vegetation in recent decades (de Jong et al., 2013), and continued change may be expected over this century (Sitch et al., 2008). Vegetation cover and composition can significantly influence the regional climate in Africa. Climate change-driven changes in regional vegetation patterns may feed back to climate via shifts in surface energy balance and the hydrological cycle, with resultant effects on surface pressure patterns and larger-scale atmospheric circulation. In this study, I used the regional Earth system model RCA-GUESS, incorporating interactive vegetation-atmosphere coupling, to investigate the potential role of vegetation-mediated biophysical feedbacks on climate dynamics in Africa in an RCP8.5-based future climate scenario. The model was applied at high horizontal resolution (0.44° × 0.44°) for the CORDEX-Africa domain with boundary conditions from the CanESM2 GCM.

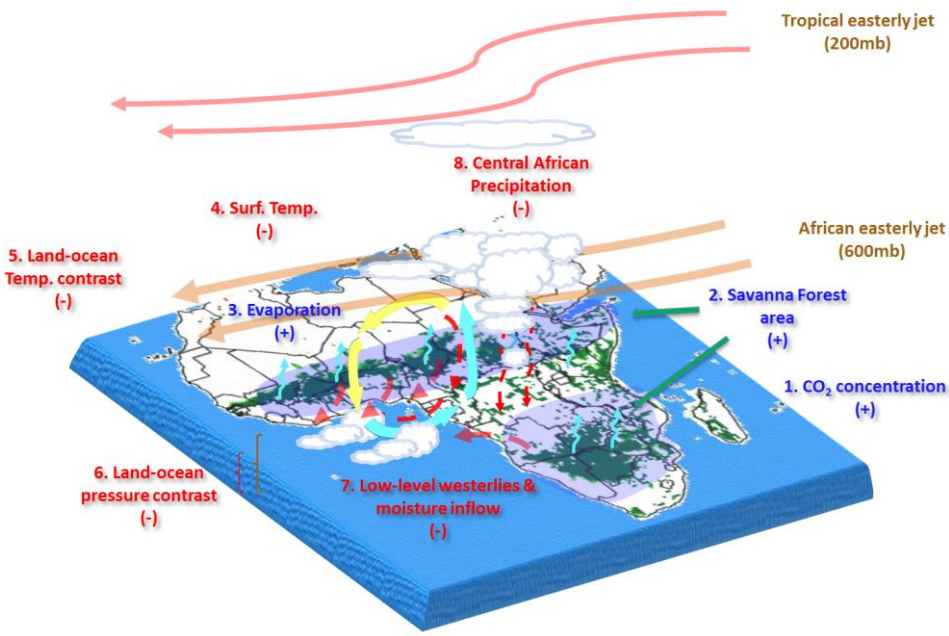

Figure 7.
Mechanisms resulting in the remote effects of the biophysical feedback on African rainfall. "(+)" and "(-)" signify increases and decreases, respectively.

I found that changes in vegetation patterns associated with a CO_2 and climate-driven increase in net primary productivity, particularly over sub-tropical savannah areas, imposed not only important local effects on the regional climate by altering surface energy fluxes, but also resulted in remote effects over central

Africa by modulating the land-ocean temperature contrast, the Atlantic Walker circulation and moisture inflow feeding the central African tropical rainforest region with precipitation (figure 7). The vegetation-mediated feedbacks were in general negative with respect to temperature, dampening the warming trend simulated in the absence of feedbacks, and positive with respect to precipitation, enhancing rainfall reduction over rainforest areas. Our results highlighted the importance of vegetation-atmosphere interactions in climate projections for tropical and sub-tropical Africa.

4.3 Evaluating Amazonian resilience by analyzing the hydrological relationship and vegetation productivity (Paper III)

The transition between arid ecosystems and moist forest in Amazonia is characterized by a strong relationship between precipitation and ecosystem gross primary productivity (GPP) and growth. By correcting for biases in internally generated climate from ESMs, this analysis revealed that global CMIP5 ESMs and empirical datasets all showed a similar relationship between precipitation and evapotranspiration, ecosystem productivity and ecosystem structure. This hydrological relationship was predicted to be relatively stable in the future, suggesting that the amount of precipitation needed to sustain moist tropical forest might be similar today and in the future. The analysis also showed that future CO_2-induced increases in water use efficiency (WUE) could increase GPP, but might not result in significant vegetation growth. Together with precipitation, land use emerged as the largest threat to the Amazon forest. However, the relatively crude resolution of the global ESMs and their biases in simulated precipitation, together with their relatively simple representations of vegetation dynamics may compromise their ability to capture the potential effects of land use on climate and vegetation changes. This motivated the study of land use impacts on regional Earth system climate and ecosystem productivity for the Amazon in Paper IV.

4.4 Impacts of LULCC on natural vegetation dynamics through land-atmosphere interactions for South America (Paper IV)

In addition to considering land surface changes induced by natural vegetation dynamics as in Paper II, and motivated by the findings in Paper III, this study incorporated anthropogenic land use, to investigate the sensitivity of land-atmosphere interaction in response to large-scale land conversion. South America is characterized by a strong interplay between the atmosphere and vegetation and land use affects the exchange of energy and water with the atmosphere. In this study, I had assessed the impact of land use on climate and natural vegetation dynamics over South America with RCA-GUESS with two simulations over the CORDEX-South America domain. The results showed that land use imposes local and remote impacts on South American climate. These included significant local warming over the land use-affected area, changes in circulation patterns over the Amazon basin during the dry season, and an intensified hydrological cycle over much of the land use-affected area during the wet season. These changes also affected the natural, undisturbed vegetation: land use led to a contrasting increase (around 10%) and decrease (up to 10%) in ecosystem productivity between northwestern and southeastern parts of the Amazon basin, respectively, caused by mesoscale circulation changes during the dry season, and an increased productivity in the wetter land use-affected areas during the wet season (figure 8). I concluded that ongoing deforestation around the fringes of the Amazon could impact pristine forest by changing mesoscale circulation patterns, amplifying the changes to natural vegetation caused by direct local impacts of land use activities.

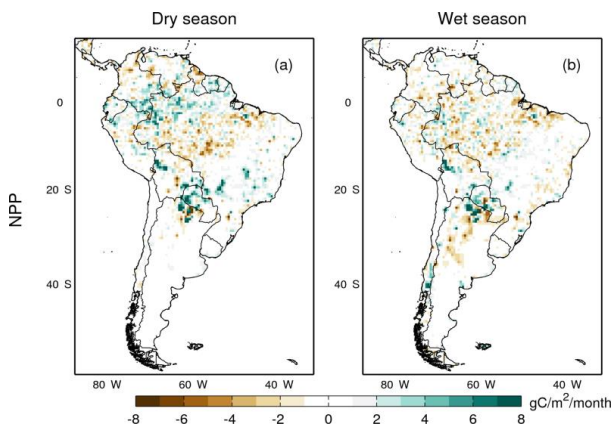

Figure 8.
Changes in Net Primary Production (NPP) of the natural vegetation resulting from land use-induced climate change for dry (a) and wet (b) seasons.

Compared to the land-atmosphere interaction study for the African tropics performed with the same model (Paper II), which revealed marked impacts of vegetation feedbacks on tropical rainfall by modulating land-ocean contrasts and mesoscale circulation, the simulated impact on circulation and its seasonality were smaller in this study. This difference may to some degree be due to the differences in simulation setup (natural vegetation changes in Paper II vs. imposed land use in Paper IV), but it was also likely associated with different regional circulation characteristics and land surface changes. As land use-induced changes in the temperature gradient between the Amazon basin and the intensive land use area in this study was almost orthogonal to the incumbent strong South American trade winds, it was not surprising that the land use impacts on precipitation in this study were smaller than for the African tropics. In the latter case, changes in circulation induced by subtropical vegetation feedback more directly counteract the original weak moisture inflow (the net change in circulation was in the opposite direction to the original wind flow), implying that LULCC over African savanna may impose greater impacts on the regional climate compared to savanna of South America.

5.Conclusion and outlook

In this thesis, based on previous achievements in the developments and applications of the regional ESM RCA-GUESS as well as its vegetation dynamics component LPJ-GUESS (Smith et al., 2011, Wramneby et al., 2010, Zhang et al., 2014, Smith et al., 2001), I extended its use to investigating regional land surface changes and land-atmosphere interactions over three different regions. This work provides potential new understanding of the roles of vegetation dynamics and socioeconomic drivers (LULCC and wildfire) in regional Earth system dynamics. In this thesis, in response to the identified research questions (see Section 2), I conclude that:

- Future changes in the fire regime over Europe driven by climate and socioeconomics changes are important for predicting future land surface changes. Fire-vegetation interactions and socioeconomic effects emerge as important uncertainties for future burned area.
- The hydrological cycle in the tropics is sensitive to land cover changes over the semi-arid areas in Africa, and biophysical feedbacks play an important role through modulating regional circulation patterns.
- Future CO_2-induced increases in WUE could increase GPP, but may not result in significant changes in the hydrological constraint on vegetation growth. Together with precipitation, land use emerged as the largest threat to the Amazon forest.
- The impacts of land use on Amazonian productivity are significant, and occur through alteration of local and regional climate.
- The sensitivity of the land-atmosphere interaction varies regionally depending on the location and the type of land cover changes.

The development of Earth system models, akin to the developments of other scientific fields, relies on the communication and interaction between different scientific communities, in which the “feedback loop” between scientific players plays an important role for advancing scientific development. Similar relationships may exist between model development and application: Model applications are usually oriented by specific questions and evaluate the model’s ability to solve those questions, providing references for the model development. Model development can then target the existing problems and in turn improve the model’s suitability for model applications. Such feedbacks build on iterative processes from which both model development and application can benefit. The regional Earth system model RCA-GUESS has shown its advantage for the studies of land-atmosphere interactions in this thesis. The results suggest that vegetation

dynamics and heterogeneity of land surface properties play important roles in shaping these interactions. A resultant outlook for both the model development and applications emerges as:

- Fire regimes are characterized as being greatly affected by extreme events such as heat and drought. RESMs have an advantage of simulating extreme events on a physical basis and may provide a more realistic framework for assessing the impact of changes than traditional GCMs or the GCM-based statistical downscaling approach. Still today, mechanistic-based fire models incorporated into RESMs are not available or they are rare despite the identified importance of fire in shaping the land surface properties as well as its possible feedbacks on local and regional climate. Studies require not only understanding of fire's response to extreme climate events and fire-vegetation interactions, including post-fire mortality and vegetation succession after fire, but also an understanding of the relationship between fire and LULCC, which still remains a challenge for the fire modelling community. Collaboration is warranted across field measurements, satellite-observation analysis, fire modelling, RESM modelling as well as research in relevant global and regional socioeconomics issues.
- Modelling land-atmosphere interaction builds on the representation of land cover details, in particular for those land cover types with large variations affecting local climate. For example, vegetation feedbacks under natural vegetation can differ considerably from managed forests and agricultural land. Studies on land-atmosphere interactions would benefit from the consideration of these land cover details, but its implementation in the LSS of RESM is still not common.
- From a technical perspective, modelling framework consistency with sufficient flexibility and complexity may be critical to the efficiency of model development as well as the ease of model application. The challenges here are not only related to how software project management is implemented, but also to scientific issues regarding the different conceptual frameworks that are applied, and how these can cooperate in common agreement. Exploring framework consistency and flexibility is expected to become increasingly important for the ESM communities.

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