ERC Starting Grant 2015
Research proposal [Part B1]
(to be evaluated both in Step 1 and Step 2)

Developing middle-range theories linking land use displacement, intensification and transitions

MIDLAND

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Proposal duration in months: 60

Land is a nexus for crucial societal and environmental challenges including food security, access to water, land degradation, biodiversity loss, and climate change. Development of solutions to balance these tradeoffs and synergies is currently hindered by the lack of theories explaining the conditions under which different pathways of land change occur and lead to different outcomes, integrating human and environmental aspects.

This project will develop and test integrated middle-range theories explaining the linkages between three of the major processes in land systems, i.e., (i) land use intensification and expansion, (ii) land use displacement and trade, and (iii) land use transitions or regime shifts. The work will focus on the emerging agricultural frontier of Southern African dry forests and savannas, which is a threatened and understudied region, and its linkages with distant places.

To overcome current limitations, the project builds on (i) experience in empirical, place-based studies, (ii) strong knowledge of social sciences and human-environment theories, (iii) rigorous inductive and deductive approaches to develop and test theories, and (iv) new ways to analyze linkages between distant social-ecological systems.

We will analyze: (i) The strategic field of actors' coalitions, institutions and distant linkages in emerging frontiers; (ii) Links between land use displacement, leakage, and local land changes; (iii) Pathways of agricultural expansion and intensification in tropical landscapes; and (iv) The conditions for transformative governance of land systems to foster resilient landscapes that sustain ecosystem services and livelihoods. These results will then be integrated to move towards the next generation of land system science, which will be able to develop, test and be guided by theoretical models. This will contribute to more relevant insights for social-ecological systems broadly and for sustainability and other social and natural sciences.

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Section a: *Extended Synopsis of the scientific proposal (max. 5 pages)*

A. State-of-the-art and objectives

Rationale

Terrestrial ecosystems provide essential resources, including food, feed, fiber, and many other ecosystem services, and land use is one of the major forces driving global environmental change in the Anthropocene [*1*]. Human activities on land have directly affected around 100 Mkm2, leaving less than 30% of the ice-free land surface largely untouched [*2*]. The land system is thus a nexus for some of the most pressing societal and environmental challenges including food security, access to clean water and air, land degradation, biodiversity loss, and climate change [*3*]. Developing and implementing solutions to balance these tradeoffs and synergies and achieve sustainable land uses is thus central for human well-being, and requires in-depth understanding of complex land systems and land change trajectories. This understanding is the focus of the recently emerged land change science, or land systems science (LSS) [*4*].

After two decades of existence, LSS is now a mature field, which has produced a wealth of methodological innovations, empirical observations, and contextual explanations, in particular through case-studies describing drivers and impacts of land change [*5*]. Synthesis has been essentially realized through systematic reviews and meta-analyses of the quantitative importance of drivers and impacts of land change, as well as a series of prominent "box and arrows" frameworks, e.g., on the articulation of proximate and underlying drivers [*6*], social-ecological systems [*7*], or teleconnections or telecouplings – i.e., linkages between distant social-ecological systems [*8*]. But few theoretical developments have taken place within LSS. The field essentially borrows theories from other disciplines, and is largely lacking of middle-range theories – i.e., contextual generalizations which describe chains of causal mechanisms valid for explaining a relatively well-bounded range of phenomena, and the conditions or contextual factors which trigger, enable or prevent these causal chains [*9*] –, which integrate the different human and environmental aspects of the land system. This relative neglect is repeatedly highlighted as one of the major frontiers in the field [*4,5*][1], but has not been concretely addressed yet. Because of this relative lack of integrated theories in LSS, (i) design of case studies can hardly be based on theoretically-derived hypotheses to test; (ii) development of process-based simulation models is hindered, making it difficult to simulate complex interactions and feedbacks; and (iii) the relevance of LSS for governance remains largely limited to the places where studies were conducted.

Building on (i) the methodological strengths of LSS in empirical, place-based studies, (ii) in-depth knowledge of social sciences and human-environment theories, (iii) rigorous approaches to develop and test theories, and (iv) new approaches to analyze telecouplings, this project will overcome this situation, and move towards the next generation of land systems science, which will be able to develop, test and be guided by theoretical models, and thereby generate more relevant insights for social-ecological systems and sustainability science.

Objectives

The central objective of this project is to develop integrated middle-range theories explaining the linkages between three of the major processes in land systems, i.e., (i) land use intensification and expansion, (ii) land use displacement and trade, and (iii) land use transitions or regime shifts. This objective will be articulated in steps focusing on different aspects of the emerging land use frontier of Southern African dry forests and savannas biomes, and its linkages with distant regions.

These theories should be able to explain (i) how governance and other dynamics of land use change in one region generate leakage and other forms of land use displacement, (ii) how land use displacement is organized by coalitions of actors to shape land systems regime shifts and frontiers emergence, and (iii) how land use displacement, and broader forms of telecouplings including governance feedbacks, can be channelled to foster transformative changes towards sustainable land use intensification in land use frontiers.

B. Research approach

The project will pull land system science towards a theory-rich field by building on the strengths and roots of LSS, with its strong focus on empiricism. The project thus will take an inductive approach to theory

1 See also Turner II, BL, "Land System Science: Land systems, sustainability and land system architecture", keynote address at the 2nd Global Land Project Open Science Meeting, Berlin, 19 March 2014. https://www.iri-thesys.org/events/GLP-OSM2014/videos/BL_Turner_II

development, grounded into in-depth empirical studies. Theory development and testing will be based on combining a typological approach drawing on statistical tools and counterfactuals to establish causal effects of different combinations of factors, with a process-tracing approach to identify chains of causal mechanisms linking hypothesized variables to outcomes within specific case studies [6]. Analyzing causal chains will also draw deductively on existing theories proposing specific, discrete causal mechanisms. Combination of causal effects and causal mechanisms are indeed necessary to establish convincing causal explanations [*10*].

Theoretical efforts will focus on three core themes: (i) land use intensification versus expansion as alternative paths of land change; (ii) land use displacement, i.e., geographic displacement of land use corresponding to land embodied in agricultural and forestry products traded; and (iii) land use transitions or regime shifts, i.e., non-linear and structural transformations of land systems, such as forest transitions, which are shifts from net deforestation to net reforestation. These three processes constitute some of the major challenges in transformation towards more sustainable and resilient land systems. With looming scarcity of land for expansion, sustainable intensification of production systems is increasingly crucial for addressing the multiple demands for land-based products and services [*11,12*]. LSS focused originally on place-based studies and local causes of land use change, but recently started to acknowledge the growing importance of distant causes and indirect consequences of land changes across international borders [*13*]. With globalization, land use displacement and leakage – i.e., land use displacement caused by a policy or intervention to govern land uses –, emerged as major themes. Finally, despite the explicit inclusion of feedbacks and non-linear trajectories in intensification and forest transition theories, the field is still heavily framed around the notion of "drivers", focusing on one-way causal relations and linear dynamics, thus hardly integrating more complex feedbacks from land changes. Theories have been developed to explain these three types of land changes, though leaving important aspects unexplained [*11-17*]. Further, there is no convincing theory addressing the linkages between these different dynamics. Current geographic and economic theories focus either on international trade or on local land change processes, rarely linking the two. This project will specifically work across scales, by analyzing and linking dynamics at local (landscapes), regional, and global (e.g., international trade) scales. Regime shifts theory, as part of the broader resilience theory [*18,19*], will be used to improve understanding on such systemic interactions and resulting land systems transitions.

The proposal focuses on processes of land change and displacement as they condition the emergence and development of land use frontiers, i.e. areas with abundant land and natural resources relative to labor or capital, and rapid land use change [*20*]. Most studies have been focusing on corrective measures in already established and active frontiers. Here, we will focus on the initial triggers and investigate a potential frontier at its emergence. The emerging frontier studied is the dry forests and savannas regions of Southern Africa, i.e., including the countries of the Southern African Development Community, such as Mozambique, South Africa, Zambia, Angola, and others [*21*], although work in other regions will also be conducted to study distant linkages and allow for comparability and generalizability of the findings. This region is considered as one of the areas concentrating the remaining large-scale pools of potentially available cropland. Agriculture linked to global markets is still limited in the region but rapidly growing. Distant actors are increasingly mobilized, including through large-scale land acquisitions – or "land grab" –, to overcome constraints on frontier development [*21*]. Compared to humid tropics, tropical dry forests and savannas have received little emphasis in the scientific agenda, government policies and public awareness, despite their rich biodiversity and carbon stocks, and crucial importance for rural livelihoods [*22,23*]. The novelty of this project is thus to establish the knowledge for pre-emptive governance of the frontier to foster resilient human-modified landscapes that sustain ecosystem services, biodiversity and livelihoods [*24,25*].

Details and articulation of the specific steps

The overarching project is articulated in 5 steps, addressing different components of the land system with distinct perspectives and objectives (Fig. B1.1). Each step will contribute to develop and test theories to explain specific questions, and together will allow addressing the overarching questions of the project. Focused study areas within the broader Southern Africa region will be selected for the different steps, based on preliminary investigations of the fit between the specific objectives and the local contexts, as well as opportunities and contacts established. The project will run over five years. After a six months preparation and recruitment period, Step 1 (1 PostDoc for 2 years) and 2 (1 PhD for 4 years) will start in parallel. Step 3 (1 PhD for 4 years) will start six months later, to build on contacts and study areas of Project 1. Step 4 (1 PostDoc for 2 years) will start on year 3, to build on the achievements of the three previous projects. The last six months will be mainly devoted to the synthesis work (end of Step 5). By the design of the proposal and of the staff profiles, the team will be interdisciplinary and contributing with complementary skills.

The steps are strongly complementary. Step 1 on actors' dynamics and strategies, Step 2 on trade flows and land use displacement and their links with aggregate land use, and Step 3 on local pathways of land change will mutually build on each other. Step 4 will build on the understanding of the strategic field and motivations of actors, land change processes, and telecouplings, to understand how to improve governance of land systems and sustainability in the focal region and beyond. This Step will also constitute a tough test to verify that the knowledge and theories generated throughout the project can actually contribute to improve governance and transform land systems in the focal region and beyond. Step 5 will draw on the specific theories developed through the other projects to propose integrated middle-range theories of land systems. This strong integration is central to understand articulations between the different aspects and scales of social-ecological systems, and is thus a major high-gain aspect of the project. Yet, each step can achieve its specific objectives in case of failure of one step, and the central goal of developing integrated theories will still be feasible, although the precise scope and processes explained may have to be re-evaluated.

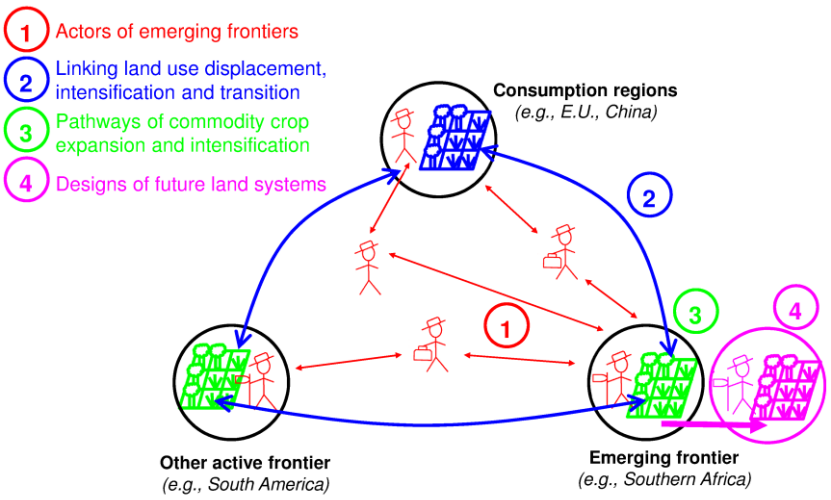

Figure B1.1. Framework of the proposal and articulation of the different steps.

Step 1: Actors' coalitions, institutions and distant linkages in emerging agricultural frontiers (PostDoc). This step will address the following questions: (i) How do distant and local actors form coalitions to create the conditions for frontiers development, and to compete for land and natural resources; (ii) What are the logics that sustain the decisions of key actors, and do they correspond to the factors hypothesized to condition frontier emergence, e.g. in the resource frontiers theory [*20*]; and (iii) How do these coalitions shape possible governance feedbacks resulting from environmental change? The general hypothesis is that the patterns of frontier development are shaped by the combination of structural factors and the agency and skills of some key individuals. Using the theory of strategic action fields [*26*], we will draw on interviews, secondary sources (on monetary flows, projects reports, and others), combined with a mapping of overlapping claims and land use competitions on the ground, to understand logics of the actors in relation with contextual factors. The step will go further than any previous study of telecoupling, by (i) combining field surveys in a specific study region, with travels and surveys in the international decision centers of the main actors and sites of origins of the telecouplings, and by (ii) broadening the scope beyond economic and political actors to include multilateral organizations, NGOs, and other private actors.

Step 2: Linking land use displacement, leakage, and land changes (PhD). This step will develop and test theories to explain (i) how do land use dynamics in a source country, in particular different pathways of forest transitions, generate land use displacement and leakage, and (ii) when does land use displacement result in intensification on already cultivated lands versus expansion of land use. Empirical relations between land use displacement and forest transitions or intensification have been shown [*27*,*28*], but no theory adequately explains these patterns. We will articulate operationalizable hypotheses along chains of causal mechanisms, to test claims from multiple competing theories explaining patterns of trade, including environmental Kuznets curve, ecological modernization, pollution haven, ecological unequal exchange, commodity chains, competitive advantage of nations, and land use theories. These hypotheses will first be explored using cross-country spatial panel analyses and structural equation modelling, with socio-economic, institutional, demographic, cultural, trade, and land use variables. Improved land use variables compared to the typically used FAO data will consist of various time series of spatially-explicit datasets already available [*30*] or under development, including by teams at UBC and the University of Minnesota. Then, we will also

use the SEI-PCS model under development [*29*], allowing to trace products exported by a country from their place of origin (e.g., municipality) to the country of destination, going beyond the current mainstream country-to-country trade analyses. Combined with spatially-explicit data from Step 3, this will allow analyzing the effects of different patterns of trade on local pathways of land change.

Step 3: Pathways of agricultural expansion and intensification in tropical landscapes (PhD). This step will develop and test theories explaining, in tropical landscapes and frontier regions, the conditions under which increased production of commodity or subsistence crops is achieved through intensification and/or expansion over different types of land uses/covers, and produces different patterns of indirect land use change (iLUC). We will go beyond the current focus on aggregate measure of land use/cover change, towards explicit analyses of both sources and sinks of land in change trajectories. This will fix major knowledge gaps on dry tropics and African landscapes, on the constraints and social and environmental risks of converting potentially available cropland to permanent agriculture, and on the conditions for sustainable intensification in frontier regions. Recent hypotheses on factors controlling pathways of commodity crop expansion, combining landscape, economic, sociological and political factors [*31*] will be tested in a set of contrasted landscapes in Southern Africa and, for comparison, in humid tropics (Central Africa and Southeast Asia). Remote sensing data, surveys, secondary statistical sources and spatial statistical analyses will be combined to measure pathways of expansion and intensification, for different crops and types of actors, to assess local displacement of land use, or iLUC, and to explain these pathways of land change.

Step 4: Transformative co-production of future land systems in frontier regions (PostDoc). Policy recommendations in LSS typically propose marginal adjustments, rather than transformative changes. We will develop a process of land use planning which (i) brings together public and private actors operating at different scales, from global to local, (ii) builds on the recent proposals to integrate LSS with landscape planning through "land systems architecture", (iii) accounts for tradeoffs between local and global sustainability issues, (iv) integrates emerging private-led and market-based instruments of land use governance. Building on the knowledge generated through the other steps, actors identified in Step 1 will be approached to participate to a series of workshops, supported by mapping, tradeoffs analyses and scenario development. Various visions of land uses will be explored, including possibilities for sustainable large-scale, capitalized commodity crops operations as well as diverse forms of agroecology and smallholder resilient land systems. Positive visions for sustainable intensification will be developed, as well as understanding of current barriers. Building on frameworks from resilience science [*32*], the goal will be to build methodological toolboxes and theoretical supports to understand the conditions under which deliberate transformative changes in land systems governance in the focal region and beyond can be fostered.

Step 5: Integrative theory of land use intensification and expansion, land use displacement, and transitions (Applicant). The applicant will organize, coordinate and directly contribute to the different steps to (i) lead each of them to achieve their specific objectives, (ii) maximize the synergies in terms of contacts, data collected and processed, and knowledge, and (iii) adjust the articulation of the different steps over time to ensure that their outputs are complementary. This step will also synthesize the outputs of the other ones, to develop integrated middle-range theories explaining the linkages between land use intensification and expansion, land use displacement and trade, and land use transitions or regime shifts.

Impacts and expected outcomes. This project will contribute to regenerate LSS, and open doors for new research avenues. Theories linking land use intensification, displacement and transitions will be relevant for other contexts and places, by (i) generating testable hypotheses to explore through multiple case studies, taking stock of recent developments to analyze comparability and representativeness of cases, such as the GLOBE tool [*33*], (ii) feeding land change simulation models with processes to implement, and (iii) showing the moderating effects of different contexts on governance interventions. We will set up the standards for future works in terms of developing contextual theories based on case studies, formulating testable hypotheses and testing them using empirical data. Theories and knowledge more specifically developed on the focal region will also be useful to understand and more sustainably govern the dynamics of land use in other active or emerging frontiers, and in other regions with land use competition between commodity crops for distant markets and smallholder agriculture for local uses. Knowledge generated will also improve the representation of the tradeoffs and indirect impacts of climate change mitigation strategies based on land use in Earth system science. Theories developed for land systems could thus strongly contribute to further theoretical developments in social-ecological systems in general.

Collaborations. The project will be primarily run by the applicant and his team, supported by multiple collaborations, including with teams of scientists working on land use and development / environment issues

in Southern Africa (e.g. Dr C. Ryan at Edinburgh University), on land use intensity, material flows and international trade (e.g., Drs K.-H. Erb and H. Haberl at Alpen-Adria University, Drs G. MacDonald, K. Carlson and others at University of Minnesota), on land changes in various other regions (e.g., Drs T. Kuemmerle and others at Humboldt University in Berlin, N.I. Gasparri at Tucuman University, Y. Le Polain at Stanford University), and on resilience science (teams at Stockholm Resilience Centre). Collaborations with Earth system and macro-economic modelers (e.g., Dr S. Luyssaert at LSCE and Prof. T. Hertel at Purdue University) will allow to compare the inductive generalizations about global land change dynamics drawn from this project with process-based modelling experiments. The goal of pulling LSS towards a more theory-supported and theory-generating field will also be achieved through broader collaborations and outreach within that community and related ones, including through the Global Land Project within Future Earth. Along the course of the project, workshops with external experts in land system and sustainability science will be organized to discuss, improve and if necessary reorient the running of the project.

C. Summary of innovative elements. The project will:

- Take stock on existing specific theories, to **develop and test integrated social-ecological systems theories** addressing **land use intensification, displacement and transitions**.
- Build on the strengths of LSS in empirical studies, while fixing gaps and **establishing a clear precedent for theory development and testing in LSS**, pulling the field to the next generation.
- Explicitly analyze **cross-scale linkages between local, regional and global dynamics**.
- Address breakthrough topics, including pathways of **commodity crop expansion in dry biomes in Africa**, conditions of **emergence of resource frontiers**, and **potentially available cropland**.
- Perform truly **transdisciplinary research**, combining positivist and hermeneutic approaches, and generating methods and **knowledge to transform governance** of social-ecological systems.
- Be directly linked and relevant to **major international networks** and communities such as the Global Land Project and Future Earth.
- Provide **methodological advances to analyze cross-scale and distant social-ecological linkages**, including linking land change and international trade with **subnational trade data**, and understanding **both local and distant actors' strategies**, and governance feedbacks.

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ERC Starting Grant 2015
Research proposal [Part B2)]
(not evaluated in Step 1)

Part B2: *The scientific proposal* (max. 15 pages)

A. State-of-the-art and objectives

1/ State of the art

Land and terrestrial ecosystems provide essential resources, including food, feed, fiber, and many other ecosystem services. At the same time, land use is one of the major forces driving global environmental change in the Anthropocene [*1,2*]. Human activities have directly affected around 100 Mkm2 of the ice-free land surface leaving, as of today, less than 30% of the land surface largely untouched [*3*]. Of this, between 23 and 38 Mkm2 (18-29% of the land surface) has been deliberately converted, mainly by deforestation, for agriculture, infrastructure and urban use, and 55-75 Mkm2 (42-58% of the land surface) have not experienced land cover conversion but are managed to satisfy human demands. Many land use practices result in ecological detriments, including land degradation, biodiversity loss, and climate change. The land system is thus a nexus for several of the most pressing societal challenges including food security and access and availability of clean water and air [*4-6*]. Developing and implementing solutions to balance these tradeoffs and achieve sustainable land uses is thus central for human well-being, and requires in-depth understanding of complex land systems and land change trajectories.

Land change science, or land systems science (LSS), has recently emerged as a part of sustainability science, studying land change and interactions between society and terrestrial ecosystems through land use [*7,8*]. LSS has been very successful to produce a depth of empirical observations, descriptions and contextual explanations, mostly through case-studies where both the drivers and impacts of land change are observed and linked in terms of causal relationships [*9*]. Synthesis of these case-studies has been performed mainly by systematic reviews and meta-analyses of the frequency of the different drivers and impacts of land change [*10,11*], and by the development of a series of "box and arrows" frameworks, including the "proximate causes / underlying drivers" framework [*12,13*], Ostrom's social-ecological systems [*14*], driving forces / actors [*15*], ecosystem services [*16*], telecouplings – i.e., interconnections between social-ecological systems that are separated geographically – [*17*], coupled human and natural systems [*18*], and frameworks to analyze land use intensity [*19*]. But few theoretical developments have taken place within LSS, and the field is largely lacking of middle-range theories which can explain the conditions under which different pathways of land change occur and lead to different outcomes. This relative neglect of theoretical developments is often highlighted as one of the major frontiers in the field [*7,9*][2], but little concrete steps have been taken to address this challenge. This deficiency is rooted in several causes including (i) a focus on local case studies, favoring interpretations strongly rooted on local contexts and an emphasis on contingent factors; (ii) a data- and method-driven focus triggered by the emergence and rapid improvements of remote sensing and other geospatial datasets, analysis techniques and computer capacities; (iii) the absence of an overarching paradigm, so that with the interdisciplinary character of LSS, scientists have mainly borrowed theory from their background disciplines, e.g., geography, landscape ecology, economics, anthropology, to guide their research on land systems. These disciplines provide useful lenses to understand land change but integrated theories which specifically capture the full human and environmental dimensions of land system dynamics still remain to be developed. This proposal will overcome these deficiencies by (i) embedding local case studies into a cross-scale research design, with explicit recognition and analysis of linkages between local and global land changes, and contextual generalization, (ii) building on a rigorous approach for theory development and an in-depth knowledge of social sciences and human-environment theories, and (iii) developing integrated middle-range theories as a step forward in the progressive development of an overall paradigm for land systems science.

With much of the research in LSS being concerned about understanding the causes and consequences of land changes, an adequate conceptualization of causal analysis is crucial for progress in theory development. Yet, the field is lacking a structured way to apprehend causal explanations, and the terminology used for causal analysis remains imprecise, with terms such as "drivers", or (spatial) "determinants" [*20*], which hint at

2 See also Turner II, BL, "Land System Science: Land systems, sustainability and land system architecture", keynote address at the 2nd Global Land Project Open Science Meeting, Berlin, 19 March 2014. https://www.iri-thesys.org/events/GLP-OSM2014/videos/BL_Turner_II

causal relations without clearly articulating them [*21*]. Causal explanation in case studies often bears similarities with historical accounts, appearing to provide *ad hoc* explanations rather than generalizable knowledge. A consistent terminology and structured approaches for articulating the conjunction of both causal effects and causal mechanisms would improve causal explanations [*21*]. The approach to theory development taken in this proposal relies on "middle-range theories" [*22*], or "typological theories" [*23*], which essentially identify contextual generalizations describing chains of causal mechanisms valid for explaining a relatively well-bounded range of phenomena, and the conditions or contextual factors which trigger, enable or prevent these causal chains.

Land use intensification, displacement and transitions constitute the three core themes which will be the focus of theoretical development in this proposal. Several theories have thus been developed to explain these three types of land change, but they leave important aspects unexplained, and do not address linkages between these three dynamics. Research on land systems focused originally on place-based studies, and on endogenous processes and local causes of land use change. Land use intensification – broadly defined as increasing inputs and/or outputs per unit of land used [*19*] – was among the few fundamental land use process which was articulated in theory, with the progressive development of theories of induced intensification [*24-26*]. Other important theoretical developments on intensification address the conditions under which intensification may lead to a rebound-effect, i.e. trigger increased demand for land-based products and land use expansion, instead of sparing land for nature by concentrating production on a smaller land area [*27-31*]. It has been shown that the remaining "potentially available cropland" – i.e., productive land that could be used for rainfed farming with moderate capital investments, and that is neither under intensive use, legally protected, nor under mature forest cover –, present important constraints and social and environmental trade-offs to being converted [*32*]. With such looming scarcity of land for expansion, sustainable intensification of production systems is increasingly crucial for addressing the multiple demands for land-based products and services [*28,33,34*]. Most theories of intensification insufficiently account for socio-political factors affecting the choices between expansion and intensification, and focus either on smallholders pre-industrial systems producing for subsistence and local markets, or on economic processes in agriculture well integrated into global markets. Yet, in developing countries, especially in agricultural frontiers, many different actors with various characteristics and assets, including smallholders and highly capitalized and industrial operators, coexist in rural landscapes, and produce crops for local and distant markets. In these landscapes, expansion and intensification dynamics are linked in complex ways [*35*].

Forest cover change has also been a focus of theorization efforts. Though several economic and socio-political theories exist to explain deforestation [*36,37*], integrated theories remain to be developed. Theories of forest transition and land use transitions represent one of the very nice theoretical progresses developed essentially within LSS. Forest transition theories, still perfectible but now firmly established on empirical and conceptual grounds, propose contingent generalizations to explain shifts from net deforestation to net reforestation at national or regional scale [*38-42*]. Land use transition theory and the related socio-metabolic theory are more akin to grand theories, i.e. high-level and very abstract narratives positing macro-level patterns. These theories posit a general sequence of shifts in land use from wildlands to frontier clearing, smallholder subsistence farming, and progressive intensification and urbanization, along with economic development [*43*], and a corresponding non-linear relation between human appropriation of net primary production and population along with industrialization [*44*].

Progressively, several streams of research have converged to identify the growing importance of distant causes and indirect consequences of land use changes as they arise across international borders and in the context of differing national policy and socio-economic regimes [*45*]. With globalization, land use displacement – broadly defined as a geographical shift of land use from one place to another, e.g. corresponding to the land use embodied in traded agricultural and forestry products –, and leakage – i.e. land use displacement caused by a policy or intervention to govern land uses –, emerged as major themes [*46*]. Trade theories, including economic geography and agricultural economics theories, partly explain displacement processes, but do not clearly articulate the links with local land change processes – i.e., land use intensification, expansion and transition –, and insufficiently account for non-economic factors of land use. So far no theory is clearly able to explain the conditions under which (i) land use displacement occurs, (ii) in particular, a forest transition is associated with land use displacement, and (iii) an intervention to protect ecosystems in one place results in leakage.

Finally, despite the explicit inclusion of feedbacks and non-linear land change trajectories in theories of land use intensification and forest transitions, most of the field is still dominated by the "proximate / underlying drivers" framework [*12*], which focuses mainly on one-way causal relations and linear land changes. This framework hardly integrates feedbacks from land changes and more complex interactions in land systems.

Regime shifts theory, among other aspects of resilience theory more broadly [*47-50*], is emerging as one useful perspective on land systems [*51*], which can provide further understanding on such systemic interactions and resulting transitions. As social-ecological feedbacks from consequences of land change to their drivers often depend on perceptions and decisions from agents of land change, understanding these feedbacks requires more refined theories of environmental cognitions and decision-making – i.e., how human perceive and react to environmental change [*52*].

One specific focus of the proposal is on understanding the processes of land change and displacement as they condition the emergence and development of land use frontiers. Frontiers can be defined as areas possessing "unusually abundant natural resources and land relative to labor or capital" [*53*], and characterized by high rates of land use and cover change. Theories of forest and land use transition address regime shifts at the bottom of the land use curve, i.e. intensification and release of land for nature when the land use frontier is closed (Fig. B2.1). Here we will focus on the top of the curve, the initial triggers for land use development. With globalization, large-scale actors of land use can increasingly operate in exploitative modes, moving from one frontier to another faster than governance actors do react, similarly to "roving bandits" in marine ecosystems [*54*]. The main emerging frontier on which the project will focus is the dry forests and savannas regions of Southern Africa.

A general premise of the project is to recognize that we essentially live in a used planet [*55*], and that with complex relations between nature and land use, there are opportunities for human-modified landscapes that sustain ecosystem services and biodiversity [*56-59*]. Therefore, the objective is not to maintain the current status-quo situation, but rather to accompany a process of anthropogenization of the landscapes in a sustainable and resilient manner, conserving crucial ecosystems and their services and improving local livelihoods. In this view, sustainable intensification is not simply about minimizing environmental impacts, but more broadly transformation towards land systems which addresses the multiple dimensions of sustainability, including food security and power issues [*60*].

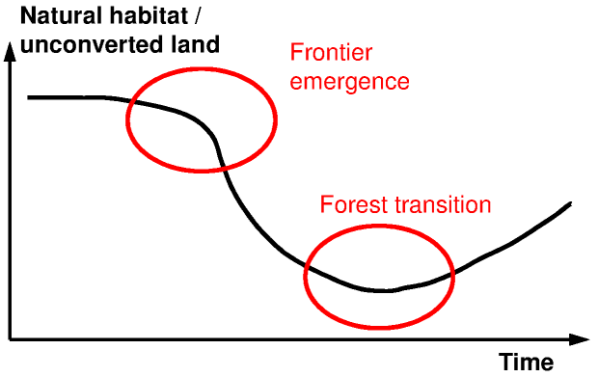

Figure B2.1. Different types of regime shifts in land systems.

2/ Objectives

The central objective of this project is to develop integrated middle-range theories explaining the linkages between three of the major processes in land systems, i.e., (i) land use intensification and expansion, (ii) land use displacement and trade, and (iii) land use transitions or regime shifts. This objective will be articulated in steps focusing on different aspects of the emerging land use frontier of Southern African dry forests and savannas biomes, and its linkages with distant regions.

These theories should be able to explain (i) how governance and other dynamics of land use change in one region generate leakage and other forms of land use displacement, (ii) how land use displacement is organized by coalitions of actors to shape land systems regime shifts and frontiers emergence, and (iii) how land use displacement, and broader forms of telecouplings including governance feedbacks, can be channeled to foster transformative changes towards sustainable land use intensification in land use frontiers.

Through this central objective, the targeted spillover objectives and outcomes of this project are (i) to push land system science towards a more theory-supported field, setting up the standards for future works in terms of developing contextual theories based on case studies, formulating testable hypotheses and testing them using empirical data and formalizing them into simulation models; (ii) to address a series of breakthrough topics, including pathways of commodity crop expansion in Africa and in dry biomes, conditions of emergence of resource frontiers, potentially available cropland, empirical studies of actors and decision-

making strategies giving rise to telecouplings, and transdiciplinary studies of land systems [*61*]; and (iii) to contribute to transform governance of land systems in the emerging frontier region of Southern Africa and in regions linked, to improve sustainability, livelihoods, and agricultural production.

To paraphrase Box and Draper [*62*], all theories are wrong, but some are useful. Because of the current relative neglect of theoretical development in LSS, (i) design of case studies can hardly be based on theoretically-derived hypotheses to test; (ii) development of simulation models strongly relies on pattern-oriented rather than process-based approaches, hindering the simulation of complex interactions and feedbacks [*63*]; and (iii) the relevance of LSS for governance remains largely limited to the places where studies were conducted. This project will thus contribute to regenerate the field, and open doors for new research avenues. Theories linking land use intensification, displacement and transitions will be relevant for multiple other places and contexts, by (i) generating testable hypotheses to explore through multiple case studies, taking stock of recent developments allowing to analyze comparability and representativeness of cases [*64*], (ii) feeding land change simulation models with processes to implement, and (iii) highlighting general dynamics, feedbacks and distant or indirect linkages that require governance interventions. Given the relevance of land management for Earth system dynamics, improved understanding of the linkages between land cover conversion and intensification in different places through displacement will open perspectives for improved representation of the tradeoffs and indirect impacts of climate change mitigation strategies based on land use [*3*]. Land systems constitute one clear archetype of the broader social-ecological systems (SES). Theories developed for land systems could thus strongly contribute to further theoretical developments in SES in general.

Theories and knowledge more specifically developed on this focal region will also be useful to understand and more sustainably govern the dynamics of land use in currently active frontiers, as well as in other potentially emerging ones, such West, Central and East Africa; boreal or arctic regions potentially opening to agriculture or other land uses with climate change; regions of Southeast Asia such as Burma and Papua New Guinea; other dry tropical regions, and more generally other regions with land use competition between commodity crops for distant markets and smallholder agriculture for local uses.

B. Methodology

General approach. The objective of the project is to pull land system science towards a theory-rich field by building on the strengths and roots of LSS, with its strong focus on empiricism. Thereby, the project will combine a deductive approach drawing on existing theories with an inductive approach to theory development, grounding theoretical efforts into in-depth empirical studies. Drawing on its multidisciplinary nature, another fundamental feature of LSS is its combination of multiple approaches and sources of data, including remote sensing, census and secondary statistical sources, spatial analysis techniques, household surveys, interviews and other qualitative data, field measurements, trade flows, and others. The overarching project is thus articulated in 5 steps, which will all address different components of the land system (Fig. B1.1). These steps provide complementary perspectives on the processes of land use expansion, intensification, competition, displacement and transition. Each step will contribute to develop and test theories to explain specific questions related to different aspects of the land system, and together, these pieces will allow addressing the overarching questions of this proposal. The steps will draw on the different streams of theories reviewed above, as well as on various theories relevant to understand the decisions of agents, which have not been so far mobilized to understand land systems. The general approach is based on the premise that, to fully understand land systems as social-ecological systems, it is necessary to combine the understanding of structural factors with that of the agency and decision-making strategies of the actors [*65,66*]. The Step 1 focuses on understanding the role of agency in land changes, and structural factors related to the social field in which actors interact, i.e., on the role of different actors and institutions, local and distant, in creating and shaping the emergence of a land use frontier. The Step 2 focuses on broader socio-economic structural factors of land change, to develop and test theories to explain (i) when does land use displacement result from leakage versus other causes, and (ii) when land use displacement results in intensification or not. The Step 3 focuses on understanding the factors which explain the pathways of expansion and intensification of agriculture in tropical landscapes, including different types of land over which expansion occurs, as well as the outcomes of these pathways. The Step 4 will develop a transdisciplinary process for land use planning in frontier regions, building on the knowledge gained in the other steps. The Step 5 will ensure the articulation of the other steps, and synthesize the results to develop and integrative theory of land use displacement, expansion and intensification, and transitions.

Focal study region. The main emerging frontier on which the project will focus is the dry forests and savannas biomes of Southern Africa, which constitute a particularly interesting place for this project for several reasons. Most work on land use change in frontier regions has been conducted in already established and active frontiers, mainly in humid tropics [*67-69*]. Agriculture linked to global markets is still very limited in the Southern Africa, but rapidly growing, among others soybean production with growing influence of distant actors from China, Europe, and South America, but also multilateral organizations such as the World Bank [*70*]. In relation to that, this region is also a major focus of interest and activities related to large-scale land acquisitions – or "land grab" [*71,72*]. Southern Africa is considered as one of the areas concentrating the remaining large-scale pools of potentially available cropland [*32*]. Dry forests and biomes are relatively neglected in the scientific agenda, and no study details sources of land and pathways of commodity crop expansion in Africa [*35*] High conservation priority is attributed to humid tropical forests, but tropical dry forests, savannas, shrublands and grasslands have received comparatively little emphasis in government policies and public awareness [*73,73*]. Yet, these regions are rich in biodiversity, including many endemics, and harbor globally important carbon stocks, but being also characterized by a sparse network of protected areas, they are among the most threatened ecosystems worldwide [*73,75*]. Southern African savannas and dry forests contain astonishing biodiversity, including some of the last large wilderness complexes of the world and an array of charismatic large mammals [*76,77*]. Protected areas are increasingly threatened by degazettement for expansion of agro-industrial production of profitable commodities [*78*]. Dry biomes also provide crucial resources for rural livelihoods [*79,80*].

In sum, here, we will investigate a potential frontier before it emerges, when rates of land use and cover change are still low, but when increasing focus and actors mobilization suggest that emergence might occur if some constraints are overcome [*70*], so that the region is likely to increasingly become a nexus of land use competition [*81*]. The goal and novelty of this project is thus to establish the knowledge and conditions for pre-emptive governance of the frontier, rather than post-hoc corrective measures.

More focused study areas within that broader region will be selected for the different steps, based on preliminary investigations of the fit between the specific objectives and the local contexts, as well as opportunities and contacts. Mozambique currently appears as a particularly dynamics country, with contacts already established. Although Southern Africa will be the main focal region, in order to study linkages with other regions, as well as to allow for comparability and generalizability of the findings to broader contexts, work in other regions will also be conducted.

General approach for development and testing of middle-range theories. Following Merton [*22*], the premise adopted here is that it is premature to directly aim at proposing an overarching paradigm for land system science, which is inherently an interdisciplinary field encompassing multiple dimensions of social-ecological systems. Instead, middle-range theories are proposed as an intermediate step to progressively build generalized knowledge. Such theories provide governance lessons valid in well-specified contexts, thus navigating between the double pitfalls of purely contingent lessons on one hand, and panaceas on the other hand [*82*]. Theories on causal explanations of land change will be established through inductive generalization, by combining evidence of causal effects with reconstruction of the causal mechanisms [*21*]. The former will be established based on statistical tools and counterfactuals analyses, to build typologies of combinations of factors leading to specific outcomes. The latter will be reconstructed using the process-tracing approach, which relies on decomposing and validating, for internal consistency and empirically, each step of the causal chain linking hypothesized causal factors to an outcome; testing additional implications that should be valid if the theory is correct; and invalidating counter-hypotheses [*23*]. A deductive approach drawing on existing theories will serve to both formulate hypotheses and support specific, discrete causal mechanisms along the causal chains.

Contacts and collaborations: The project will be primarily run by the PI and his team, yet also working through multiple collaborations for specific parts. Collaborations with scientists already working in Southern Africa on land use and development / environment issues will be important to establish the work in the study region. Contacts already established include among others Drs C. Ryan and E. Mitchard (University of Edinburgh) and Dr S. Dondeyne (University of Leuven). Other contacts in the region are currently being established. Ongoing work with Dr J. Godar (Stockholm Environment Institute) and a broader team around the development of the SEI-PCS model to trace products exported by a country from their place of origin (e.g., municipality) to the country of destination [*83*] will be useful for Step 3. Collaborations with several teams at Stockholm Resilience Centre will be useful for Step 4. Other ongoing collaborations with teams working on land use intensity, material flows and international trade, land changes in South American, Southeast Asian and Central African frontiers and in Europe and Central Asia, as well as with Earth system and macro-economic modelers, will be useful throughout the project (see part B1). Multiple collaborations

within the land system science, Earth system science and sustainability science communities will ensure that the theoretical developments aimed by this project will benefit from and to efforts of a larger community.

Risk management strategy: Beyond typical risks associated with empirical research and LSS, several main risks were identified. First, the study region constitutes a difficult working environment in environmental and human terms. The selection of the staff working on the project will thus require special care, to ensure that people hired do have the personal characteristics to be able to work in such environments. Trustful collaboration with teams already working in the region and with local authorities will be crucial to allow the project to operate. The PI will draw on his experience among others in establishing a strong network of collaborations in Vietnam during his PhD, and in other countries during several postdocs. Second, a strong added value will come from the integration of the different perspectives provided by the individual steps. In case of failure of one step, however, each individual steps' objectives retain value in themselves, and the central goal of developing integrated theories will still be feasible, although the precise scope and processes explained by these theories may have to be re-evaluated.

Step 1: Actors' coalitions, institutions and distant linkages in emerging agricultural frontiers (PostDoc, 2 years)

Objectives: To understand the role of different actors and institutions, local and distant, in creating and shaping the emergence of a land use frontier.

Profile required: A researcher experienced in at least (i) land system science – including geomatics, theories of agricultural and land use change, social-ecological systems, tropical land uses – , or (ii) social sciences theories and methods of fields analyses, institutional analysis and social networks [*84*], and able to rapidly integrate the other component. Experience in fieldwork in tropical/developing regions, as well as ability to interact with high-level decision-makers will be necessary. A PostDoc researcher is thus required.

Relevance to the complete proposal and articulation with the other steps: This step will focus on agency, as well as structural factors related to the social field in which actors of land use interact. We will build on the data and knowledge gathered by other steps, to understand how actors constitute the link between trade flows (Step 2) and pathways of land use change (Step 3). The understanding of the strategic field and motivations of actors will feed into the process of land use planning (Step 4), and will contribute to the general theorization efforts (Step 5).

Rationale and novelty: The issue of telecouplings, i.e. linkages between distant social-ecological systems, is an emerging key issue to understand sustainability in a globalized world [*45,85,86*]. Such telecouplings have already been studied by looking at flows of material [*87,88*], but no study so far has analyzed such distant linkages by directly connecting surveys and interviews of both distant and local actors, with the local land change realities, to reconstruct and understand the strategic action field in which actors operate and its consequences on land use.

Several recent hypotheses and theories will be tested and refined, including the hypothesis of increasing couplings between production frontiers by actors operating in different regions and integrating horizontally across different land use sectors [*89*], as well as the "resource frontiers" theory which lists the necessary conditions for frontier emergence – i.e., the presence of abnormal rents due to institutions repressing the "normal" returns to labor; economic, political or technological changes allowing for transitory windfall profits from resource exploitation –, and the conditions necessary for long-term development of a frontier – i.e., ensuring that profits from resource exploitation are invested in other activities and a diversification of the economy, and promoting linkages between the resource extraction and other sectors of the economy [*53*]. This step will also explore the factors and processes conditioning the possible emergence of "telecouplings feedbacks", i.e. responses involving distant actors to govern the social and/or environmental issues created by the frontier emergence. Such form of governance feedback is frequently mentioned as a key element in telecouplings frameworks [*85,86*], but has never been studied in detail. A recent hypothesis proposed that such feedback leading to successful systemic transformation occurs when focusing events trigger coalitions between – mostly local – actors driven by "defensive environmentalists" behaviors – i.e., self-oriented reactions to threats directly affecting their own well-being – and possibly more distant actors motivated by "altruistic environmentalism" – i.e., the reinterpretation of the same issues in terms of global sustainability –, leveraging this reaction to advocate for broader governance changes [*90*]. As stated above, regime shifts is an emerging topic in land science, currently mainly focusing on forest transitions or collapses and socio-economic shocks [*91,92*]. Here the study will contribute to understand shifts of land use regime from mainly agriculture for subsistence and local markets towards the start of large-scale land changes related to distant

factors (Fig. B2.1). Finally, by bringing the understanding of the actors' logics into a field of LSS dominated by a positivist approach, the goal is also to reinforce the hermeneutic perspective to social action related to land and the environment.

Methodology: The major questions that will be explored are: (i) How do distant and local actors form coalitions to create the necessary conditions for the development of the frontier, and for positioning themselves in the incoming competition for land and natural resources; (ii) What are the logics that sustain the decisions of key actors, and do these rationales correspond to the structural factors hypothesized to lead to frontier emergence; and (iii) How do distant and local actors possibly form coalitions to shape the governance feedback resulting from the frontier emergence? The hypothesis that will be tested is that, beyond macro-socioeconomic and agroecological factors addressed in Step 2, the emergence, patterns and outcomes of this frontier development are shaped by (i) structural factors related to the strategic action field in which the actors navigate, and (ii) the agency and skills of some key individuals.

We will mobilize the theory of strategic action fields [*84*], which proposes a framework to describe the different actors in a field or social space (e.g., incumbents, challengers, governance units) and the structural conditions which constrain and support their actions. It also proposes hypotheses about (i) how fields emerge, persist and transform, in particular through "episodes of contention", influenced by the skills of different actors to form and maintain broad coalitions, and (ii) how different fields in different spaces and scales are linked together. The research will draw on interviews and secondary sources (on monetary flows, projects documents and reports, investment profiles, and others), to understand logics of the actors in relation with the geographic, economic, political and cultural context of the field. The study will involve field surveys in the study region itself – i.e., Southern Africa, with a focus on a more specific subregion –, but also several travels and contacts with the international decision centers of the main actors, public and private, or to sites of origins of the telecouplings (e.g., farms in operation in South America, with projects in Southern Africa; sites of demand for products in China or Europe; decision centers of international organizations, depending on the identified key actors). This will be combined with a mapping of actor's decisions and land use competitions on the ground, with overlapping claims by different actors and different land uses on land and its resources [*93*]. By directly surveying distant actors influencing land use in the study region, and by broadening the scope of the actors surveyed to include not only economic and political actors but also multilateral organizations, NGOs, foundations and other private actors, this research will go further than any other study on telecoupling.

Expected outputs: (i) A comprehension of the strategic action field of land and natural resource competition in the emerging frontier of Southern Africa and in one specific place in particular; (ii) General hypotheses tested in the study area and testable in other contexts on the role of coalitions of local and distant actors in shaping land change, on the conditions that control the emergence of land use frontiers and land use regime shifts, and on the conditions that control the emergence of a telecoupled feedback from environmental change involving local and distant actors; (iii) Contribution to Step 4 with insights on how actors would react to governance interventions including land use policies and market-based or supply chain-oriented instruments or interventions on distant actors; (iv) Understanding of the socio-economic tradeoffs and conflicts, possible winners and losers in the study region (in combination with Step 3).

Step 2: Linking land use displacement, leakage, and land changes (PhD, 4 years)

Objectives: To develop and test theories to explain (i) when does land use displacement result from leakage versus other causes, and how different pathways of forest transition result in more or less land use displacement or leakage, and (ii) when land use displacement results, in the sink region, in intensification on already cultivated lands versus expansion of land use.

Profile required: A graduate in geography, land system science, environmental science, ideally with skills in spatial econometrics, industrial ecology and social science theory.

Relevance to the complete proposal and articulation with the other steps: The social field in which land use actors interact (Step 1) is nested in broader socio-economic and political fields [*83*]. This step will contribute to the complete proposal by untangling the broader structural relations between forest transitions, land use displacement and land use changes, thereby complementing the perspective in Step 1 focusing on agency and field-specific structural factors. The patterns of international land use displacement observed in this step will be compared with more fine-scale and detailed data on gross land use changes from Step 3 for places studied in both projects, in order to further understand the relation between land use displacement and

local land changes. The theories generated and tested will be used to account for possible distant effects of future land systems developed in Step 4, and will contribute to the general theorization efforts (Step 5).

Rationale and novelty: This step will provide major breakthrough in the theoretical agenda in LSS, by analyzing structural relations between three central issues of contemporary land systems, i.e. land use intensification, displacement, and forest transitions. First, several works showed an empirical relation between forest transitions and different forms of land use displacement and leakage, but these works also showed that these relations are very heterogeneous and context-dependent [*87,94*], and currently no theory has been able to adequately explain these patterns. Similarly, recent works highlighted relations between land use displacement and intensification, but these relations remain unclear [*95*]. One major recent theoretical progress on this topic formalized the economic conditions under which intensification may result in land sparing or not, and thus possibly land use displacement [*31*], but does not account for non-economic factors and does not address the reverse relation, i.e., the consequences of land use displacement on intensification in the sink region (the region absorbing the land use displaced from another region). Beyond these efforts, works have explored the relation between various macro-sociological theories related to trade and processes of land change, mainly deforestation [*96-98*]. In contrast with these works, we will test claims from multiple competing theories rather than one theory at the time, and we will articulate detailed hypotheses along a causal chain to reconstruct the hypothesized causal mechanisms. This will allow properly sorting out competing theories, and reconciling convergent claims from different theories [*21,23*]. Further, these works generally rely on coarse data on land use. We will combine several macroeconomic and macro-sociological theories (see below) with detailed data and knowledge on land change, to understand the interactions of economic, social, political, cultural and biophysical factors.

Methodology: Following the objectives above, the research will focus first on theories linking land use displacement and leakage with processes occurring in the source region – i.e., the region which displaces land use elsewhere, typically a forest transition region. Then, a second set of studies will focus on theories linking land use displacement with intensification and expansion of land use in the sink region.

We will start by establishing a set of operationalizable hypotheses on these processes, based on a series of theories identified as addressing these topics, including the theory of environmental Kuznets curve (EKC, [*99,100*]), ecological modernization [*101,102*], pollution haven [*103-106*], ecological unequal exchange [*107-110*], comparative and absolute advantage, commodity chains [*111,112*], competitive advantage of nations [*113*], new economic geography [*114,115*], as well as land use theories including forest transition and intensification theories discussed earlier.

These hypotheses will be explored using cross-country panel datasets of socio-economic, institutional, demographic, cultural, trade, and land use variables. The inclusion of cultural variables (e.g., on environmental attitudes, [*116,117*]), as well as improved land use data compared to the typically used FAO data will constitute two breakthroughs of this project. These improved land use data will consist of various sources, including data for the period 2000-2010 on gross forest cover change [*118*], and other time series of spatially-explicit datasets on agricultural changes currently under development by Prof. N. Ramankutty at UBC and at the Institute on the Environment in the University of Minnesota. These datasets will be analyzed with spatial panels, structural equation modelling and other statistical approaches.

For the second part of linking displacement with land use changes in sink countries, a set of subnational study areas, including areas studied in Step 3, will be analyzed using the SEI-PCS model under development [*83*]. This model allows to trace products exported by a country from their place of origin (e.g., municipality) to the country of destination (thus going beyond country-to-country assessments which form the current mainstream trade analyses). Combining this model with spatially-explicit data on land use change, in particular those generated by Step 3, will allow to analyze the effects of different patterns of international trade on local pathways of land use change, and conversely, how patterns of international trade of different commodities are influenced by heterogeneous local contexts.

Expected outputs: (i) Theoretical propositions, tested empirically, to explain the conditions under which processes internal to a source country generate land use displacement and leakage, and in particular the relations between different pathways of forest transition and such displacement and leakage; (ii) Theoretical propositions, tested empirically, to explain when land use displacement results in expansion of land use in the sink region versus intensification in already cultivated lands.

Step 3: Pathways of agricultural expansion and intensification in tropical landscapes (PhD, 4 years)

Objectives: To understand the factors which explain the pathways of increase in agricultural production in tropical landscapes, between intensification and expansion over different types of land, as well as the outcomes of these pathways.

Profile required: A graduate in geography, land system change, environmental science, with skills in remote sensing, spatial analyses, socio-economic surveys, and developing countries rural contexts.

Relevance to the complete proposal and articulation with the other steps: This step will contribute to the complete proposal by untangling the factors which produce different pathways of land change in frontier regions, and thereby showing how the actors' strategies (Step 1) and the structural patterns of land use displacement manifest themselves in producing landscape changes. Knowledge on the different actors of land use and structural factors affecting their decision (Step 1) will contribute to explain the pathways of land change observed in this step. The relations between land use displacement and land use change observed at coarse scale (country or subcountry) in Step 2 will be compared with fine-scale, detailed data on gross land use changes for smaller landscapes from this step, to further understand the relation between land use displacement and local land changes. The theories generated and tested will be used to reflect on possible future pathways of land change in the focal region of Step 4, and will contribute to the general theorization efforts (Step 5).

Rationale and novelty: The focus of research and governance efforts on tropical land use change has been on humid tropics [*119*]. Processes of land change in dry tropics have started to be documented mainly in South American frontiers (e.g., Gran Chaco and Cerrado [*120-123*]), but remain poorly documented in Africa [*124*]. But increasingly, as humid tropics become increasingly protected [*119*], land change and frontiers expansions shift from humid to dry tropics biomes as these regions become the focus of investors' efforts [*70*]. This research will strengthen the knowledge on dry tropical landscapes and land uses by comparing their dynamics with those of humid tropics. The study will also push for a second-generation of land change studies, which goes beyond the aggregate measure of land use/cover change (e.g., overall amount of deforestation in a landscape, [*12*]), towards explicit analyses of bivariate trajectories of land change accounting for both sources and sinks of land changes (i.e., gross land use/cover changes analysed through matrices of changes), recognizing that gross pathways of land change have crucial implications for the environment and livelihoods [*35*]. Improved understanding of land changes in dry tropical regions will also allow to better assess the constraints and social and environmental risks of converting potentially available cropland to permanent agriculture, which is a central issue to evaluate what forms of agricultural expansion are possible with relatively low negative impacts [*32*]. Finally, current theories of land use intensification, such as induced intensification theory, as well as the resource frontiers theory [*53*], although recognizing multiple causal factors, generally consider that intensification is less likely in contexts where land resource is very abundant compared to population and capital. Studying both expansion and intensification will allow exploring the conditions to achieve sustainable intensification in frontiers.

Methodology: We will start with a recently developed set of hypotheses on factors controlling pathways of commodity crop expansion [*35*], which articulate the effects of four main groups of factors: (i) the availability of suitable forestland, which is determined by forest area, agroecological or accessibility constraints, and land use policies, (ii) economic and technical characteristics of agricultural systems, (iii) differences in constraints and strategies between actors, in particular small-scale and large-scale ones, and (iv) variable costs and benefits of forest clearing. These hypotheses combine economic theory with landscape, sociological and political factors.

A set of landscapes will be selected, with different biophysical, institutional and socio-economic contexts, including two landscapes located in the focal study region of dry biomes of Southern Africa, and two other landscapes in humid tropical biomes for comparison, one in Central Africa and one in Southeast Asia (the former to maintain specificities of the African context, the latter to provide an external benchmark in a region with which the PI is familiar). In each landscape, remote sensing data will be used to measure gross land use/cover changes and sources of new cropland for production of different commodity crops – i.e. crops mainly produced for distant markets – and crops for subsistence and local markets. Land use intensification for different crops and actors will be measured by secondary statistical sources and surveys when necessary. Spatial statistical approaches will be used to assess the local displacement of land use, or iLUC, possibly

resulting from land use expansion [*125,126*]. Explanatory factors will be measured with secondary sources and surveys of the different actors of land use. Spatial statistical analyses will then allow explaining the pathways of land change (expansion on different types of land, intensification in situ, indirect land use changes) based on the observed factors.

Expected outputs: Typological theories identifying, in tropical landscapes and frontier regions, the conditions under which (i) increased production of commodity or subsistence crops is achieved through intensification and/or expansion, (ii) expansion occurs over different types of land uses/covers, and (iii) commodity crop expansion produces different magnitudes and patterns of land use displacement or indirect land use change.

Step 4: Transformative co-production of future land and food systems in frontier regions (PostDoc, 2 years)

Objectives: To understand the conditions under which governance of land systems in the focal region can be improved, and develop a transdisciplinary process of land use planning involving local and distant actors for pro-active governance and deliberate transformation of an emerging land use frontier.

Profile required: A researcher skilled in geography, land system science, environmental science, landscape ecology, land use planning, and political ecology, and with experience of developing countries institutional and environmental contexts. Skills in communication and negotiation, and experience in working outside academia and/or in transdisciplinary science, would be very useful. A PostDoc researcher is thus required.

Relevance to the complete proposal and articulation with the other steps: This step will build on the achievements of the Steps 1-3 in terms of understanding the actors and institutions, land change processes, and telecouplings, to further test the knowledge generated, and understand to what extent it can contribute to actually improve governance of land systems and sustainability in the focal region and beyond.

Rationale and novelty: In early developments, land system science focused primarily on delivering policy recommendations for public actors (local and national governments, international organizations), in particular for governing land systems through land zoning and agricultural and forestry policies [*127*]. Recently, the importance of a more diverse range of interventions, including private-led, market-based and incentive-oriented approaches to more sustainably organize land use has been highlighted [*128,129*]. But although these recent works recognize that real governance is generally hybrid [*130*], these two streams of scholarship remain largely separated, and few models exist to articulate traditional land use policies, including land zoning and land use planning, with emerging private-led tools. Further, typical policy recommendations in LSS address marginal changes in the land systems, rather than transformative changes to resilient and adaptive social-ecological systems [*47,131*]. This research will integrate land system science with landscape planning, along the recent proposals to develop "land systems architecture" [*132*]. In contrast with traditional land use planning, we will develop a process of "trans-scalar land use planning" [*133*], i.e. a process which (i) brings together public and private actors influencing directly or indirectly the land systems in the focus region, but typically operate at different scales, from global to local, (ii) takes into account tradeoffs between local realities and broader sustainability issues, and (iii) integrates emerging private-led and market-based instruments of land use governance. This research will thereby also push the agenda for transdisciplinary sustainability science, recognizing that developing methods, theoretical supports and approaches to co-produce transformative changes in land systems is a field of research in itself [*61*].

Methodology: The research will take place in a focal area within the broader study region of Southern Africa, selected based on the outcomes of the Steps 1-3, and will rely on frameworks recently developed in resilience science to foster deliberate transformative changes on social-ecological systems [*131*]. The different actors identified in Step 1 will be approached to participate to a process of land use planning proceeding through a series of workshops and meetings, with works related to mapping, analysis and scenario development by the researcher in between. Understanding of pathways of land change (Step 3) will be mobilized to explore possible consequences of different scenarios on landscapes, and understanding of linkages between local land changes and land use displacement (Step 2) will be mobilized to explore possible consequences of land changes in the focal region on the rest of the world. The process of trans-scalar planning will be original in that it will not only consider the outcomes of land use planning and land systems architecture for local actors and livelihoods, but will also consider the possible visions that other, distant actors may have for that region, and, symmetrically, the possible visions that the local actors may have about how their region may contribute goods and services to distant places – through agricultural and forestry production, ecosystems services, or others –, as well as about how the rest of the world is expected

to contribute to development of sustainable land uses in their region. We will explore various visions of land uses and land systems, including the possibilities for sustainable large-scale, capitalized commodity crops operations as well as diverse forms of agroecology and smallholder resilient land systems, and will seek to develop positive visions for sustainable intensification. Indeed, most of the work on biodiversity and ecosystem services in human-modified landscapes has been focused on relatively densely populated and settled landscapes [*56-59*]. Here we will explore how these ideas can be applied to contexts with lower population density and where rapid large-scale land use change by industrial actors is an increasing concern.

Expected outputs: (i) Improved understanding of a possible approach for trans-scalar land use planning and implementing land systems architecture, with methodological toolboxes and theoretical supports; (ii) Positive scenarios and established preconditions for future improvements in land systems governance in the focal region and beyond.

Step 5: Integrative theory of land use intensification and expansion, land use displacement, and transitions (Applicant, 5 years, 50%)

Objectives: To coordinate the different steps, and integrate their results to develop integrated middle-range theories explaining the linkages between land use intensification and expansion, land use displacement and trade, and land use transitions or regime shifts.

Relevance to the complete proposal and articulation with the other steps: Through this step, the applicant will, first, organize, coordinate and directly contribute to the different steps in order to (i) lead each of them to achieve their specific objectives, (ii) maximize the synergies in terms of contacts with different actors, data collected and processed, methods implemented and knowledge generated so that each step's objectives can be facilitated by the work done in other ones, and (iii) adjust the articulation of the different steps over time to ensure that their outputs can complement each other. Second, the outputs of the different projects will be synthesized.

Rationale and novelty: Over two decades, land systems science has accumulated a wealth of empirical knowledge and methodological innovations to monitor, analyze and model land systems and social-ecological systems more broadly, but generalizations are mainly limited to box-and-arrows frameworks and meta-studies providing quantitative summaries of various empirical relationships. It is now time to move towards the next generation of land systems science, which will be able to develop, test and be guided by theoretical models, and thereby contribute to generate more relevant insights for sustainability, as well as theories that can be relevant for other fields in studies of social-ecological systems, sustainability science and other social and natural sciences.

Methodology, including overall project management: In terms of integrating the results of the different steps, the theoretical efforts will focus on several core issues. First, by understanding the conditions under which land use displacement occurs, separating between leakage and other forms of displacement, as well as the role of forest transition pathways and the effects of this displacement on the sink region in terms of intensification and expansion (Step 2), the project should be able to formulate the conditions under which (or processes by which) sustainable forms of land uses can be established in one region without generating unsustainable forms of land use displacement elsewhere. Second, by understanding (i) the role of structural factors and agency of coalitions of local and distant actors in shaping the emergence of land use frontiers and land use regime shifts, as well as possible related telecoupled governance feedbacks (Step 1), and (ii) the conditions under which frontiers emerge through different pathways of intensification and/or expansion, over different types of land uses/covers, and with different indirect land use change and environmental and social effects (Step 3), the project should be able to formulate the conditions under which landscapes which are not yet intensively managed can be partly protected for wilderness, and partly shaped into sustainable anthropogenic landscapes (Step 4).

The project will run over five years (Table 1), starting by a six months preparation and recruitment period, after which Step 1 (PostDoc) and 2 (PhD) will start in parallel. Step 3 (PhD) will start six months later, to take stock of contacts and selection of study areas already operated by Step 1. Step 4, which will build on the achievements of the three previous projects, will start on year 3 at mid-time of the project. The last six months will be mainly devoted to the synthesis work (last pieces of Step 5). PhDs cover four years, which is the standard in Belgium. Both PostDocs cover two years, which is necessary for in-depth work.

Beyond that, day-to-day interactions, as well as more formal activities (annual team retreats, internal workshops) will be organized to ensure that the multiple linkages between the different steps are effective. A share of the budget (see below) is provisioned for organizing two workshops (in year 2 and 5) with a panel of

external experts in land systems science, to present, discuss, improve and if necessary reorient the running of the project. By the design of the overall proposal and of the staff profiles, the team will be interdisciplinary and contributing with complementary skills, and the recruitment process will ensure that this complementarity is realized, and takes into account a diversity of profiles not only in terms of skills and disciplinary backgrounds but also of personal characteristics. Diversity in terms of gender, countries of origin, age and careers pathways will be highly beneficial for such a project which touches on core issues at the interface between Earth system challenges and local livelihoods priorities, and interdependencies and possible conflicts between and within developed, emerging and developing regions.

The overall goal of pulling land systems science towards a more theory-supported and theory-generating field will also be achieved by organizing and participating to various activities (workshops, conference sessions, summerschools…) to discuss the ideas and approaches generated in this project, confront them to other perspectives, and showcase the relevance of this approach. These activities will mainly be supported by third-party sources, e.g. SESYNC, and the participation of the applicant to the Scientific Steering Committee of the Global Land Project within the Future Earth umbrella, which currently constitutes the largest and most cutting-edge network of land systems scientists.

Expected outputs: (i) Achievement of the objectives of each specific step, with associated peer-reviewed papers and other outlets to disseminate the results, (ii) Middle-range theories able to produce testable hypotheses on linkages between land use intensification and expansion, displacement and transitions in different contexts, (iii) Establishing a clear precedent for theory development and testing in land system science, thereby pulling the field to the next generation.

Table 1: Timeline of the project

	Year 1		Year 2		Year 3		Year 4		Year 5	
Months:	1-6	6-12	12-18	18-24	24-30	30-36	36-42	42-48	48-54	54-60
Step 1										
Sites selection, identification of actors and contacts										
Data collection										
Analyses										
Step 2										
Hypotheses formalization, selection of countries										
Country-scale land use, trade and other data collection										
Cross-country analyses										
Subnational sites selection and data collection										
Linking subnational and international trade to land use change										
Synthesis and thesis writing										
Step 3										
Sites selection and contacts										
Data collection in Southern African landscapes										
Analyses in Southern African landscapes										
Data collection in comparison landscapes										
Analyses in comparison landscapes										
Synthesis and thesis writing										
Step 4										
Site selection, establishing contacts										
Wks 1: Identifying issues and stakeholders										
Understanding of the dynamics of land change										
Wks 2: Designing a vision of future land system										
Possible outcomes of this vision (local and distant)										
Wks 3: Feedbacks from these outcomes on the vision										
Step 5										
Selection of sites, establishing contacts, hiring researchers										
Animation of the team										
Synthesis steps and theory development										

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