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From the Pixel to the Globe

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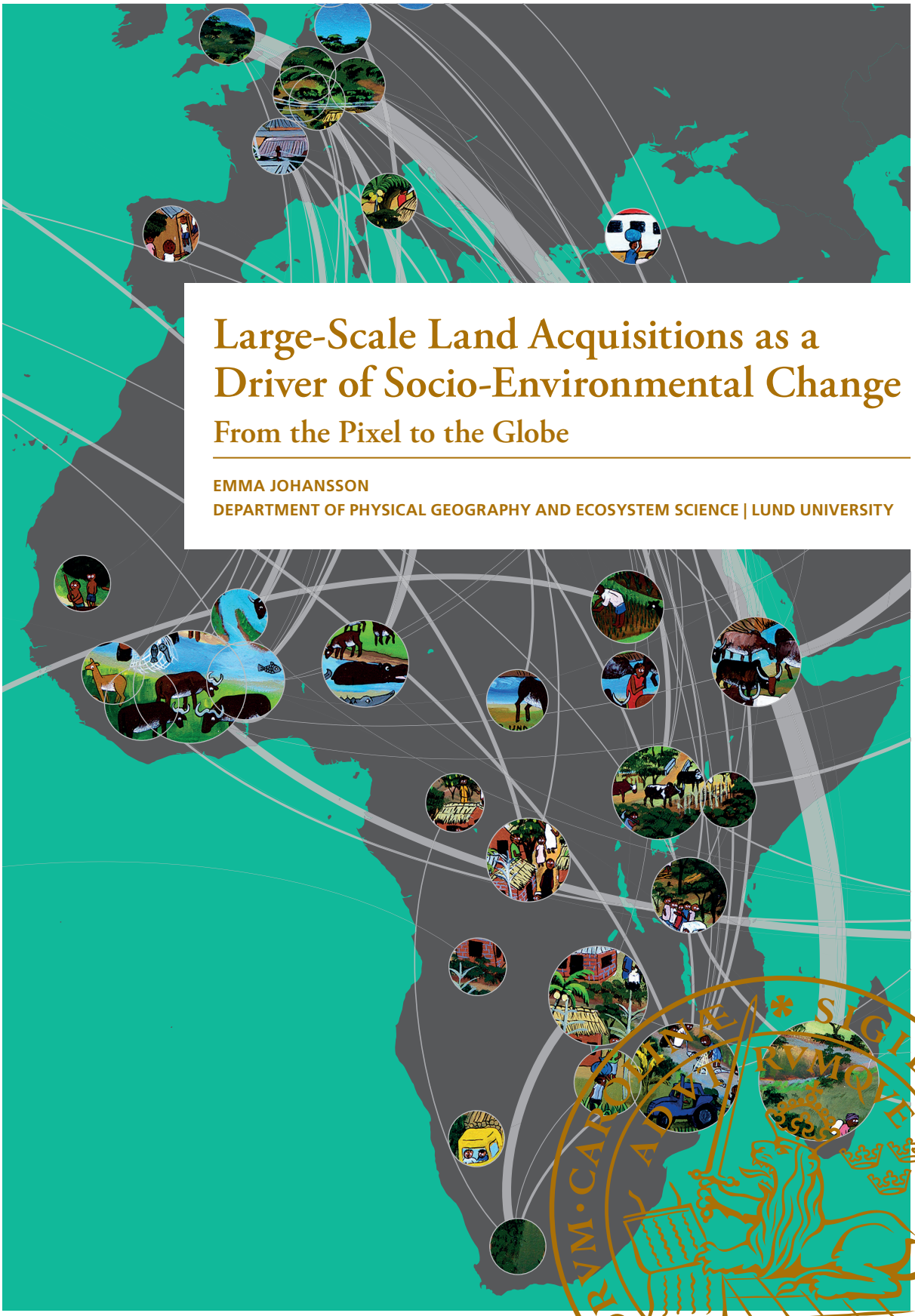

Large-Scale Land Acquisitions as a Driver of Socio-Environmental Change

From the Pixel to the Globe

EMMA JOHANSSON
DEPARTMENT OF PHYSICAL GEOGRAPHY AND ECOSYSTEM SCIENCE | LUND UNIVERSITY

Around the globe, and particularly in low-income countries, large tracts of land are acquired by foreign and domestic actors for the production of food, biofuel crops and non-edible forestry. This huge shift in land ownership from small-scale farmers to large-scale users has widespread and long-term implications for people and the environment.

In this thesis I examine drivers, impacts, and feedbacks of land system change in areas that experience large-scale land acquisitions. I do this from a global to local analytical entry point, and outline global relations between countries, land deals with high water requirements in Africa, as well as local experiences and spatial quantification of socio-environmental change in Tanzania.

Emma Li Johansson is a physical geographer interested in understanding both the social and the natural dimensions of land system change and sustainability.

LUND UNIVERSITY CENTRE OF EXCELLENCE FOR INTEGRATION OF SOCIAL AND NATURAL DIMENSIONS OF SUSTAINABILITY (LUCID).

LUCID is a Linnaeus Centre at Lund University. It is funded by the Swedish Research Council Formas, comprises six disciplines from three faculties and is coordinated by LUCSUS as a faculty independent research centre. Research aims at the integration of social and natural dimensions of sustainability in the context of grand sustainability challenges such as climate change, biodiversity loss, water scarcity and land use change. The scope is broad, the ambition is bold and the modes of operation are collaborative. Over the course of ten years we will develop sustainability as a research field from multidisciplinarity to interdisciplinarity to transdisciplinarity.

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and Ecosystem Science
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Large-Scale Land Acquisitions as a Driver of Socio-Environmental Change

From the Pixel to the Globe

Emma Li Johansson

LUND UNIVERSITY

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Abstract:

A major challenge of our time is to sustainably produce food and other goods for a growing global population, without putting additional pressures on land and water resources and local people's quality of life. Large-scale agriculture has brought many benefits to humanity in terms of food production but has also caused multiple sustainability challenges, including land and water degradation, deforestation, and biodiversity loss in areas of production. In order to better inform consumers, producers, and other decision- and policy makers about trade-offs between agricultural production and socio-environmental change, there is a need to better understand land system change across spatial and temporal scales. This requires interdisciplinary and creative research that can integrate both social and natural dimensions of sustainability. This dissertation investigates socio-environmental change in the context of large-scale land acquisitions, by integrating natural- and social science methods at different scales of analysis.

The four papers of this dissertation investigate the drivers, impacts and feedbacks of large-scale land acquisitions from the general global perspective, to the detailed local case study. *Paper I* explores the global connectivity of large-scale land acquisitions in terms of virtual land export and import. The land-trade pattern is visualised and analysed as a network, which reveals that a few countries are responsible for providing network connectivity (China, the UK, and the US), while Africa is the most targeted region. We highlight that the network structure is prone to propagate socio-environmental risks and vulnerability for both importers and exporters of land. These results led to the development of *Paper II*, which is an in-depth analysis of water requirements for crops currently grown on acquired land in Africa. We used a dynamic vegetation model (LPJmL) to model blue and green water requirements of crops in order to identify hotspots of blue water use (irrigation water from e.g. groundwater, rivers, dams) that indicate areas of high risk for water-related conflicts. We found that crops grown on acquired land require more water than traditional crops, and even with the most efficient irrigation system 18% of the land acquisitions would be blue water hotspots. *Paper III* aims to better understand the local context in which land acquisitions occur, exploring people's perceptions of change in Kilombero Valley, Tanzania. Participatory methods were used to discuss and visualise perceptions of socio-environmental change, which point to rapid degradation of forests and wetlands. This is explained as a coupled effect of large-scale land acquisitions (farmers are forced off their land and need to find other areas for farming), population growth (more people have to share less land for farming), and areas set aside for conservation (prohibiting expansion of farmland). *Paper IV* complements and compares the experienced socio-environmental changes with land change detection, using satellite images. We found that local perceptions of farmland expansion to the wetland area align with the land change detection, while narratives of rapid deforestation could not be identified in the satellite images. This underscores the need to integrate qualitative and quantitative methods (so-called mixed methods) in order to find strengths and limitations within scientific knowledge production.

Based on the findings of this dissertation, I suggest that crops grown on acquired land should be edible, and primarily produced to increase local and domestic food security. I also suggest that crops planted should be suitable for that local climate, and low in water requirements in order to avoid water conflicts. If agribusinesses use irrigation, the irrigation systems should be of highest water use efficiency. Consequently, if land acquisitions are to be considered as investments, they must be at the forefront of exploring more sustainable pathways of farming, by accounting for local needs, improving environmental conditions, and applying the latest scientific knowledge, no matter the economic cost.

Key words: large-scale land acquisitions; telecoupling; socio-environmental change; land system science; network analysis; environmental modelling; participatory research; remote sensing; mixed methods

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From the Pixel to the Globe

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"Land has become scarce now since people have increased in this area. People are forced to cultivate the same piece of land over and over again, and this has lead to decreased productivity and fertility of the land, so the soil quality has also decreased. This together with the decreasing water levels and changes in the rain, has lead to drying of the land. So, land is more dry than it used to be in the past."

Farmer interviewed during fieldwork in Kilombero Valley, Tanzania, March 2015

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Abstract

A major challenge of our time is to sustainably produce food and other goods for a growing global population, without putting additional pressures on land and water resources and local people's quality of life. Large-scale agriculture has brought many benefits to humanity in terms of food production but has also caused multiple sustainability challenges, including land and water degradation, deforestation, and biodiversity loss in areas of production. In order to better inform consumers, producers, and other decision- and policy makers about trade-offs between agricultural production and socio-environmental change, there is a need to better understand land system change across spatial and temporal scales. This requires interdisciplinary and creative research that can integrate both social and natural dimensions of sustainability. This dissertation investigates socio-environmental change in the context of large-scale land acquisitions, by integrating natural- and social science methods at different scales of analysis.

The four papers of this dissertation investigate the drivers, impacts and feedbacks of large-scale land acquisitions from the general global perspective, to the detailed local case study. *Paper I* explores the global connectivity of large-scale land acquisitions in terms of virtual land export and import. The land-trade pattern is visualised and analysed as a network, which reveals that a few countries are responsible for providing network connectivity (China, the UK, and the US), while Africa is the most targeted region. We highlight that the network structure is prone to propagate socio-environmental risks and vulnerability for both importers and exporters of land. These results led to the development of *Paper II*, which is an in-depth analysis of water requirements for crops currently grown on acquired land in Africa. We used a dynamic vegetation model (LPJmL) to model blue and green water requirements of crops in order to identify hotspots of blue water use (irrigation water from e.g. groundwater, rivers, dams) that indicate areas of high risk for water-related conflicts. We found that crops grown on acquired land require more water than traditional crops, and even with the most efficient irrigation system 18% of the land acquisitions would be blue water hotspots. *Paper III* aims to better understand the local context in which land acquisitions occur, exploring people's perceptions of change in Kilombero Valley, Tanzania. Participatory methods were used to discuss and visualise perceptions of socio-environmental change, which point to rapid degradation of forests and wetlands. This is explained as a coupled effect of large-scale land acquisitions (farmers are forced off their land and need to find other areas for farming), population growth (more people have to share less land for farming), and areas set aside for conservation (prohibiting expansion of farmland). *Paper IV* complements and compares the experienced socio-environmental changes with land

change detection, using satellite images. We found that local perceptions of farmland expansion to the wetland area align with the land change detection, while narratives of rapid deforestation could not be identified in the satellite images. This underscores the need to integrate qualitative and quantitative methods (so-called mixed methods) in order to find strengths and limitations within scientific knowledge production.

Based on the findings of this dissertation, I suggest that crops grown on acquired land should be edible, and primarily produced to increase local and domestic food security. I also suggest that crops planted should be suitable for that local climate, and low in water requirements in order to avoid water conflicts. If agribusinesses use irrigation, the irrigation systems should be of highest water use efficiency. Consequently, if land acquisitions are to be considered as investments, they must be at the forefront of exploring more sustainable pathways of farming, by accounting for local needs, improving environmental conditions, and applying the latest scientific knowledge, no matter the economic cost.

Sammanfattning

En av de största utmaningarna i modern tid är att på ett hållbart sätt producera mat och andra varor för en ökande global befolkning, utan att utsätta mark- och vattenresurser för ytterligare belastning och därmed ha negativ inverkan på människors livskvalitet. Storskaligt jordbruk har genererat många fördelar för människan gällande matproduktion, men har även bidragit till många hållbarhetsutmaningar, som försämring av mark och vatten, avskogning, och minskad biologisk mångfald. För att bättre informera konsumenter, producenter, och andra beslutsfattare om samverkan mellan jordbruk och markanvändningsförändring krävs en djupare förståelse för drivkrafter, effekter, och feedbacks förändringar i samhälle och natur över olika rumsliga och temporala skalor. Detta kräver interdisciplinär och kreativ forskning som kan integrera både sociala och miljömässiga dimensioner av hållbarhet. Den här avhandlingen utforskar dessa samhälleliga och miljömässiga förändringar inom kontexten storskaliga markförvärv (large-scale land acquisitions, även känt som land grabbing), genom att integrera metoder from natur- och samhällsvetenskap över olika analytiska skalor.

De fyra artiklarna i denna avhandling utforskar drivkrafter, effekter och feedbacks av storskaliga markförvärv, från det generella globala perspektivet, till den detaljerade lokala fallstudien. *Artikel I* ger en global överblick över vilka länder som virtuellt importerar eller exporterar mark genom storskaliga markförvärv. De globala markförvärven visualiseras och analyseras som nätverk, vilket visar att få länder har en stor roll i det globala nätverket (Kina, Storbritannien och USA), samt att Afrika är den kontinent där mest mark köps eller hyrs ut till externa aktörer. Vi understryker att den globala strukturen av markförvärv är benägen att sprida sociala och miljömässiga risker och sårbarhet, både för länder som importerar och exporterar mark. Dessa resultat ledde till utvecklingen av *Artikel II*, som är en detaljerad analys av hur vattenanvändning ändras in samband med markförvärv i Afrika. Vi använde en vegetationsmodell (LPJmL) för att modellera blått och grönt vattenbehov av olika grödor för att identifiera hotspots för blå vattenanvändning, vilket i sin tur kan indikera områden med hög risk för vattenrelaterade konflikter. Vi kom fram till att grödor som odlas på markförvärv kräver mer vatten än traditionella grödor, och även om de mest effektiva bevattningssystemen används så klassas 18% av markförvärven som hotspots. *Artikel III* har som mål att förstå den lokala kontexten där storskaliga markförvärv sker. Baserat på fältarbete i Tanzania användes deltagandemetoder för att diskutera och visualisera upplevda sociala och miljömässiga förändringar. Lokala erfarenheter pekar på snabb avskogning och degradering av våtmark eftersom fler människor måste dela mindre mark för jordbruk, vilket är en kombinerad effekt av befolkningstillväxt och storskaliga markförvärv. *Artikel IV* jämför de lokala

upplevelserna av förändring med kvantifieringar av marktäcke genom satellitbildstolkning. Genom denna jämförelse kan berättelserna om jordbruksexpansion mot våtmarken stärkas och kartläggas, medan den snabba avskogningen i detta fall inte kan identifieras i satellitbilderna. Detta understryker ett behov att integrera kvalitativa och kvantitativa metoder för interdisciplinär forskning, för att hitta styrkor och begränsningar inom vetenskaplig kunskapsproduktion.

Baserat på resultaten i denna avhandling föreslår jag att grödor som odlas på markförvärv ska vara ätbara, och primärt produceras för att bidra till lokal och nationell matsäkerhet. Jag föreslår även att grödor som odlas ska vara lämpliga för det lokala klimatet, och kräva lite vatten för att undvika vattenkonflikt. Om jordbruksföretag använder bevattning bör dessa system vara av bästa vatteneffektivitet. Följaktligen, om markförvärv ska kunna kallas investeringar bör de vara i framkant av en mer hållbar jordbruksutveckling, genom att ta hänsyn till lokala behov, förbättra miljö, och omsätta de senaste vetenskapliga rönen i praktiken, oavsett ekonomisk kostnad.

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The first quote of this dissertation is from a Tanzanian farmer who described to me how the availability, accessibility, and quality of farmland and water have changed since a foreign agribusiness acquired land in his village. During my visits to Tanzania, I started to reflect on vulnerability to, and responsibility for, environmental change. I realized that I am part of a society that demands products derived from natural resources elsewhere, which in turn cause increasing challenges for people who require those same natural resources for survival. With this dissertation I therefore hope to contribute with new knowledge and awareness, from a scientific perspective, of those challenges that have their roots in consumption and production in an unequal world. I do this by focussing on socio-environmental drivers, impacts, and feedbacks of land system change in the context of large-scale land acquisitions.

During the past five years, I have met so many people that have inspired, and supported me while developing this dissertation. I would like to express my gratitude to you all, and to some people in particular (sorry in advance if you feel forgotten).

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List of papers

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II. Johansson, E. L., Fader, M., Seaquist, J. W., & K. Nicholas (2016). "Green and blue water demand from large-scale land acquisitions in Africa." *Proceedings of the National Academy of Sciences,* 113(41):11471-11476.

III. Johansson, E. & E. Isgren (2017). "Local perceptions of land-use change: using participatory art to reveal direct and indirect socioenvironmental effects of land acquisitions in Kilombero Valley, Tanzania." *Ecology and Society,* 22(1).

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Contribution to papers

Paper I: EJ contributed to research design, performed most of the data preparation and analyses, and contributed to the writing of the manuscript.

Paper II: EJ designed the research, performed the analysis of the quantitative data and model output, and led the writing of the manuscript.

Paper III: EJ designed the research, performed the fieldwork, prepared and analysed most of the data, and led the writing of the manuscript.

Paper IV: EJ designed the research, prepared and analysed most of the data, and led the writing of the manuscript.

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Introduction

The world is experiencing rapid societal and environmental change. Since 1900, the global population increased fivefold from 1.5 to 7.5 billion, and is projected to reach close to 10 billion by 2050 (United Nations 2017). The growing population, coupled with unequal distribution of wealth and demands for food, energy, and other goods, has led to unsustainable patterns of land and water use, as well as dangerous rates of CO_2-emissions (Foley et al. 2011; Peterson et al. 2003; Steffen et al. 2015; Turner et al. 2007). Demand for land and water for agricultural production will only increase under current trends in population growth, shifts to more meat-based diets (Erb et al. 2009a; Kastner et al. 2012), and replacement of fossil fuels with biofuels (Goldemberg et al. 2014).

Large-scale agro-industrial expansion is a major driver of land use and land cover change, which is a key process by which humans influence the functioning of ecosystems, in turn affecting people who critically depend on terrestrial and aquatic ecosystems for food and freshwater provision (Foley et al. 2005; Lambin & Meyfroidt 2011; Turner et al. 2007). Currently, about 37% of the Earth's ice-free surface is used for agriculture (World Bank 2018). As much as food is needed for survival, modern agriculture has caused complex and multi-scalar sustainability challenges, including losses in carbon storage, wildlife habitats, and watershed degradation (Brink & Eva 2009; Foley et al. 2011; Gibbs et al. 2010). Agriculture is also responsible for up to 85% of global freshwater withdrawals, affecting downstream water users in terms of water quality, quantity and accessibility (Foley et al. 2005; Kabat 2013; Shiklomanov 2000), sometimes leading to conflicts over land and water resources (Gleick 2014; Shiva 2002).

In Sub-Saharan Africa, the world's poorest region, global development institutions like the World Bank emphasise agricultural development as a key to economic development and poverty reduction (World Bank 2007). About 70% of the population is intimately linked with land and water resources through their livelihoods as farmers (Falkenmark et al. 2004). Urgent challenges relate to extreme poverty and hunger, low access to basic infrastructure like clean water and sanitation, and low rates of sustainable industrialization (Sachs et al. 2017). The World Bank's promotion of agricultural modernization has to a large extent facilitated foreign investments in agriculture to take place in many Sub-Saharan countries, and spurred large-scale acquisition of land by agribusinesses and private investors. Some see such

investments as an opportunity for agricultural development and greater self-sufficiency, as agribusinesses can enhance food security by reducing the yield gaps, bring technological development like irrigation systems and industry, and create socio-economic benefits through employment in areas in need of economic development (Cotula 2009; Deininger & Byerlee 2011; FAO 2009). Others see such investments as controversial and raise concerns about neo-colonialism, land grabbing, land tenure rights, and negative impacts on local livelihoods (Anseeuw et al. 2013; Robertson & Pinstrup-Andersen 2010; Rulli & D'Odorico 2017). They highlight that foreign investors look for land and water resources to satisfy the needs of their own region, for example to mitigate national CO_2 emissions by planting trees elsewhere (Andersson & Carton 2017; Hunsberger et al. 2017; Lyons & Westoby 2014), or to meet directives for reducing fossil fuels by producing biofuel crops (Acheampong et al. 2017; Harnesk & Brogaard 2017; Robledo-Abad et al. 2017).

Whether they are framed as "investments" or "land grabs", large-scale land acquisitions have been at the forefront of agro-industrial expansion since 2000, and are currently a major driver of land use and land cover change, especially in low- and middle-income countries with abundant and "untapped" resources of land, water, and labour (Anseeuw et al. 2012; Borras et al. 2011; Dell'Angelo et al. 2018; Lazarus 2014). Land acquisitions involve public and private actors, including governments and agribusinesses, leasing or purchasing large tracts of land for the production of goods of their choosing (Anseeuw et al. 2013; D'Odorico et al. 2017). Even though land acquisitions were noted as far back as 2000, the phenomenon escalated in 2008 as a consequence of the global crisis in food, energy, and finance (Borras et al. 2011). Acquired land areas primarily expand into forests, grasslands, wetlands, and marginal lands, but also into areas previously used for small-scale food production (Borras & Franco 2012).

Just as there has been a "rush for land" in the Global South over the last two decades, much research has focussed on the social impacts of such agricultural expansion. Societal costs relate to the violation of local farmers' land rights, and negative effects on economic development (Bergius et al. 2018; De Schutter 2011; Dell'Angelo et al. 2017), human rights (Grant & Das 2015), land tenure (Doss et al. 2014) and food security (Nyantakyi-Frimpong & Bezner Kerr 2017; Yengoh & Armah 2015). Environmental impacts on land and water resources have remained relatively understudied (Dell'Angelo et al. 2018). Current findings however point to biodiversity loss and deforestation (Feintrenie 2014; Schoneveld et al. 2010), lost access and degradation of natural resources on which people depend for their livelihoods (D'Odorico et al. 2017; Deininger 2011), as well as reduced water availability and quality due to irrigation of water intensive crops (Chiarelli et al. 2016; Mehta et al. 2012; Williams et al. 2012). There are large knowledge gaps in the scientific literature regarding water requirements of land acquisitions (Chiarelli et al. 2016; Dell'Angelo et al. 2018; Woodhouse & Ganho 2011; Woodhouse 2012).

Investments in water infrastructure (e.g. efficient irrigation) could lead to local benefits and increased food production while also making the agricultural sector less vulnerable to climate variability (e.g. erratic rainfall). However, the long-term contracts (often between 33 and 99 years) rarely include any restrictions to water use, which might lead to drastic changes in water quality, availability, and accessibility for local, as well as distant, natural resource users (Jägerskog et al. 2012).

Large-scale land acquisitions are truly a rapidly growing force for land use and land cover change (also referred to as land system change). Seto and Reenberg (2014) underscore the need to investigate and understand a wide range of contemporary trends in global land use, which involves the growing competition for land and water resources through large-scale land acquisitions. In particular, there is a need to identify new forms of agents and practices regarding distal land connections and non-local interests in land, and to investigate the effects these global land connections have on local land use and governance.

Aim and objectives

The overall aim of this dissertation is to map, and quantify, patterns of land use and land cover change in the context of large-scale land acquisitions, as well as to clarify some of the drivers, impacts, and feedbacks of socio-environmental change. I focus on four key challenges (three empirical, and one epistemological): *the global shift in land ownership (Paper I), risks of water conflict (Paper II), local experiences of socio-environmental change (Paper III), and how to co-create knowledge about local socio-environmental change (Paper III and IV)*. I approach these challenges by analysing relational and spatial patterns as snapshots in time from global to local scales by fulfilling the following research objectives: 1) To map countries involved in the virtual trade of land through large-scale land acquisitions, and to describe their connectivity (global level), 2) To calculate water requirements of land acquisitions currently in production in Africa, and analyse how water demand has changed across a range of irrigation scenarios (continental level), 3) To document perceptions of socio-environmental change, and to visualize the narratives as paintings (local level), 4) to map and quantify land cover categories established in field with remote sensing, and to combine this land change detection with narratives of land use from the ground (local level). The aims and research questions of each paper in this dissertation are outlined in Table 1.

Table 1. Aims and research questions of articles in PhD dissertation.

Paper	Scale	Aim	
I	Global	*Describe and analyse the structure of the global land acquisition system as a network to explore the connectivity and vulnerability of involved countries.*	
		Research questions	1) What does the global pattern of large-scale land acquisitions look like, and how does it function? 2) What countries are virtually exporting and importing land? 3) Which countries dominate land trade? 4) What countries are vulnerable to changes in the land acquisition network arising from the connectivity patterns?
II	Continental (Africa)	*Delineate hotspot areas that are at risk of water conflicts due to high levels of freshwater use by large-scale land acquisitions in Africa.*	
		Research questions	1) What are the water demands from crop production of land acquisitions? 2) What areas are vulnerable to increased water stress and related water conflicts?
III	Local	*Create paintings through participatory art, in order to visualize how local farmers perceive land use changes due to large-scale land acquisitions in Kilombero Valley, Tanzania.*	
		Research questions	1) What are the most important natural resources for people who live in areas of large-scale land acquisitions? 2) How do farmers, fishermen, and pastoralists perceive that natural resources have changed since the arrival of large-scale agribusinesses? 3) What are the main reasons for socio-environmental change? 4) How do the participants want the future to develop?
IV		*Quantify land cover categories established in field with remote sensing, and compare with local perceptions of change.*	
		Research questions	1) What are the dominant narratives of socio-environmental change identified with participatory research approaches? 2) What are the land use and land cover changes between 2004 and 2014 observed with remote sensing? 3) How do local perceptions of change in forest, shrubland, grazing land, farmland, wetland, and water, compare to identified land cover changes through land cover classification of the same categories?

Conceptual background

This section introduces and defines some key concepts of this dissertation: socio-environmental change, land system change, scale, telecoupling, and co-production of knowledge. These are also key concepts within land system science that acknowledge that there is a need to explore socio-environmental connectedness, and consequences of distant natural resource use in order to address global challenges of land degradation and water conflicts (Eakin et al. 2014; Liu et al. 2013a; Seto & Reenberg 2014).

Socio-environmental interactions and land system change

A central concept in this dissertation is socio-environmental change, which is the constant and complex interaction between people and nature (Berkes & Folke 1998; Young et al. 2006). Social processes (e.g. economy, policies, demography) have impacts on ecosystems (e.g. forests, wetland), and changes in ecosystems (e.g. deforestation, water use) have impacts on people and societies (e.g. health, food security).

Land systems, in turn, are the result of cross-scale socio-environmental interactions, and land system change is both a driver and impact of socio-environmental change (Verburg et al. 2015). For example, land systems are a consequence of human decision making on local (e.g. land owners), regional/national (e.g. land use planning), and global scales (e.g. trade agreements). The combined effects of local land system changes have effects on the Earth System (e.g. climate change), which in turn cause new feedbacks on ecosystems, human-well being, and decision making (Crossman et al. 2013; Verburg et al. 2015).

Land system science is an interdisciplinary field that has emerged with the aim to understand drivers, impacts, feedbacks, and trends of land use (human use) and land cover (biophysical condition) change, and how land system change in turn affects the functioning of socio-ecological systems (Rindfuss et al. 2004; Verburg et al. 2015). Initially, the field (also called land change science) relied heavily on quantitative approaches like geographical information systems (GIS), remote sensing, and environmental modelling in order to map, monitor, and model different types,

magnitudes, and locations of land use and land cover change across spatial and temporal scales (Reenberg 2009; Rindfuss et al. 2004; Turner et al. 2007; Turner 2009). The growing interest to understand land systems in terms of natural resource governance, conflicts, and other socio-environmental trade-offs has, however, led to an increased use of qualitative ground-based approaches commonly used in e.g. political ecology (Bryant 1998; Rocheleau 2008; Turner & Robbins 2008), such as ethnography, historical narrative constructions, interviews, and participatory research approaches (Verburg et al. 2013; Verburg et al. 2015).

Scale and telecoupling

Scale

The subtitle "from the pixel to the globe" highlights the importance of scale in this dissertation. Socio-environmental change needs to be understood as an outcome of cross-scale political, economic, and ecological drivers, impacts, and feedbacks (Blaikie & Brookfield 1987; Verburg et al. 2015). Scale can be defined as the "spatial, temporal, quantitative or analytical dimensions used by scientists to measure and study objects and processes" (Gibson et al. 2000). Scale thereby includes an extent, which is the spatial area or timeframe covered in the analysis, and a resolution, which is the finest spatial and temporal level of detail at which the data can be analysed. Levels refer to the position in a certain scale (Gibson et al. 2000; Vervoort et al. 2012), e.g. national (macro), sub-national (meso), and individual (micro). For example, global scale studies might analyse a system on a national level, and country-scale studies might analyse a phenomenon on a community-based level.

Socio-environmental changes (e.g. demographic change, resource extraction and consumption) can be viewed as a consequence of cross-scale and cross-level linkages, that historically and contemporarily shape new and unique outcomes, in turn posing site-specific challenges for natural resource use and management (Boda & Ramasar 2014). The choice of spatiotemporal scale critically affects the patterns and processes that can be observed, and certain patterns might be lost if the scale of analysis is not consistent with those patterns and processes. For example, rapid (e.g. floods, droughts) and slow (e.g. sea level rise, desertification) processes operate on different spatial and temporal scales. Scale therefore also has consequences for the methodological choice, analysis, and interpretation, which might enable or restrict scientific insights.

Another scale-related challenge relates to trade-offs between *generality, realism, and precision* (Chowdhury 2013). Generality aims to identify general principles and trends with emphasis on simplicity and broad applicability, and therefore comes at the cost

of either precision or realism. Realism describes the representation of essential constructs and components of systems, and their connectivity, while precision lays in the details the components of the system can be measured and represented. Precise explanations privilege detail, nuance, and fine-scale differences rather than characterizing aggregate components, patterns, or processes. This categorization is based on a study by Levins (1966) who claims that models for predicting nature cannot maximize these three goals simultaneously, but by optimizing two of the goals (e.g. precision and realism) one must sacrifice performance in the third (e.g. generality). Similar trade-offs exist for understanding socio-environmental change in the context of large-scale land acquisitions, which is why I use different scales as analytical entry points for obtaining multiple insights on drivers, impacts, and feedbacks related to the phenomenon.

Telecoupling

According to Tobler's first law "everything is related to everything else, but near things are more related than distant things" (Tobler 1970). Socio-environmental drivers, impacts, and feedbacks can however be distant to each other in geographical space, but close to each other in relational space, which poses new challenges as to how to treat scale within land system science (Manson 2008). Globalization, teleconnections, and telecoupling are three concepts that have emerged in order to deal with increasingly distant connections between social and environmental systems.

Globalization is the socio-economic interactions between human systems over distances (Liu et al. 2013a), and has increased the speed, spatial stretch, and spatial allocation of socio-environmental change and sustainability challenges (Young et al. 2006), for example through improved transport and communication systems, and international trade (Clapp & Dauvergne 2011; Meyfroidt et al. 2013; Young et al. 2006). Even though the world is more connected than ever before, people have never been so disconnected from their individual environmental and social impacts caused by consumption (Erb et al. 2009b; Mills Busa 2013; Moran et al. 2013).

Teleconnections focus on describing distant environmental drivers of land system change (Adger et al. 2009; Friis et al. 2015; Seto et al. 2012). Specifically, the term 'teleconnections' is used in climate- and atmospheric sciences to study geographically distant (typically thousands of kilometers) climate anomalies that are related to each other through ocean-atmosphere circulations (Chase et al. 2006). An example is El Niño, which originates from high-pressure systems in the western Pacific Ocean and can have effects on precipitation and drought in the southern Great Plains in Texas (Wang et al. 2015).

Telecoupling (Eakin et al. 2014; Friis et al. 2015; Liu et al. 2013a) is a framework that has been developed in order to integrate the social dimensions of globalization,

with the natural dimensions of teleconnections, linking geographically distant and spatially unconnected places as coupled human and natural systems (Figure 1). Telecoupling is more complex than teleconnections, as it considers both the environmental and socio-economic drivers, feedbacks, and multidirectional flows that increasingly characterise interactions between people and nature. The framework is useful for understanding telecoupled land use, and tracing virtual transfers of natural resources (e.g. land, water, CO_2 emissions) that are embedded in the production and consumption of agricultural goods (Baird & Fox 2015; Eakin et al. 2014; Friis et al. 2015). Virtual, in this context, refers to natural resources that are not physically embedded in the trade of agricultural products, but that were required at some stage of production (Fader et al. 2010). Telecoupling is also useful for disentangling and understanding distant drivers and impacts of socio-environmental change across scales, such as land changes related to soybean production within and among trading countries (Sun et al. 2017), distant linkages between local land use and livelihood vulnerability in relation to global environmental change (Challies et al. 2014; Lenschow et al. 2016), and global demands for rubber that drive large-scale land-use changes in Cambodia (Baird & Fox 2015).

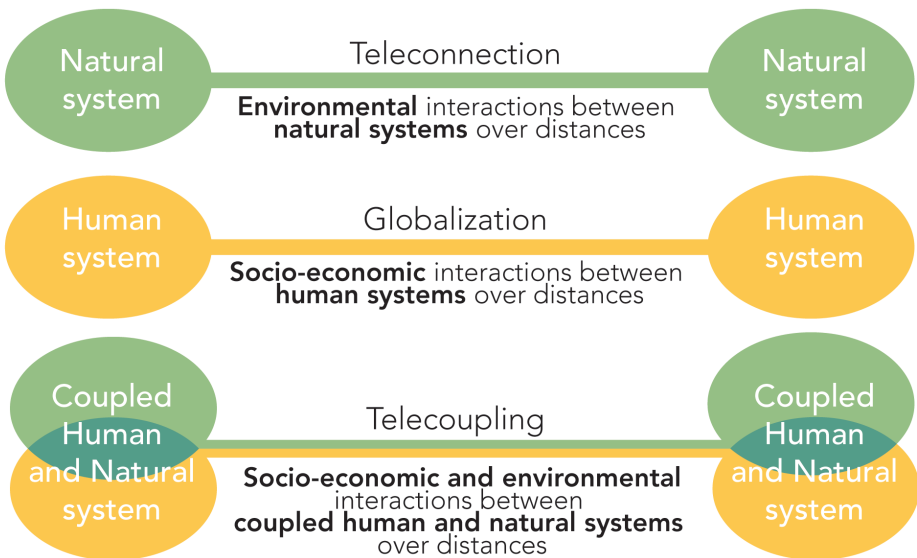

Figure 1. Definitions of teleconnections, globalization, and telecoupling. Figure adapted from Liu et al. (2013a).

Co-production of knowledge

Land system science acknowledges the need to reflect on what, and how knowledge is useful for society, and stresses the need to find new ways of integrating knowledge across the natural and social divides in science (Verburg et al. 2013; Verburg et al. 2015). Also sustainability science has such ambitions, and provides theory and insights regarding knowledge production for understanding problems of, and solutions to, sustainability challenges (Clark & Dickson 2003; Jerneck et al. 2011; Kates et al. 2001). In order to make science more useful for society, it is increasingly important to do research *with* and *for*, rather than *about* people in place (Chambers 1994; Rocheleau 2008; Rosendahl et al. 2015). Co-production of knowledge is when academic and non-academic perceptions meet, and is essential for integrating science and society in order to develop shared solutions for a more sustainable world (Pahl-Wostl et al. 2013; Pohl et al. 2010; Verburg et al. 2015). When engaging in co-production of knowledge, the traditional role of the scientist as an expert is replaced by a more equal role in learning from, and incorporating, experiences and knowledge from local partners/participants (Berkes 2010; Bryant 1998; Robbins 2003; Zurba & Berkes 2013). For example, the research focus and questions might be developed in field, as opposed to entering a case study area with a predetermined agenda and set of questions. Co-production of knowledge can therefore enable people most vulnerable to socio-environmental change to inform the researcher about the most pressing challenges, which can make the research focus more relevant for that local context, and socially robust as a whole, since it is based on local concerns (Rosendahl et al. 2015).

Study area

This chapter presents the study area of this dissertation, which stretches over global to local domains. The first paper is global in its scope, focussing on large-scale land acquisitions as a global land trade system. The second paper is continental and focus on large-scale land acquisitions that are in operation in Africa. The third and fourth papers are local in their scope, focussing on Kilombero Valley in Tanzania as case-study area.

Africa on a global land market

Large-scale land acquisitions are truly a global phenomenon. Since 2000, land has been acquired in most continents of the world: Africa, South America, Central America, Asia, (Eastern) Europe, and Oceania (Figure 2). The land acquisitions are mainly for agribusiness purposes, by multi-national corporations, investment funds, or government-owned companies (D'Odorico et al. 2017; Zoomers 2010). Currently about 69 million hectares (ha) of land have been acquired globally (estimated by Land Matrix (2018)), which equals the combined size of France and Costa Rica. Most land has been contracted in Africa (33 million ha, equal to the size of Vietnam), particularly the Eastern, Western and Central African regions. There is, however, a large difference between how much land that is contracted (i.e. current area that has been leased or purchased by the investor), and how much that is in production (i.e. land area that is already operational). About 21% of globally acquired land is estimated to be in production, which equals the size of Bangladesh. However, only 3.6% of the contracted land in Africa is currently in production (Figure 3).

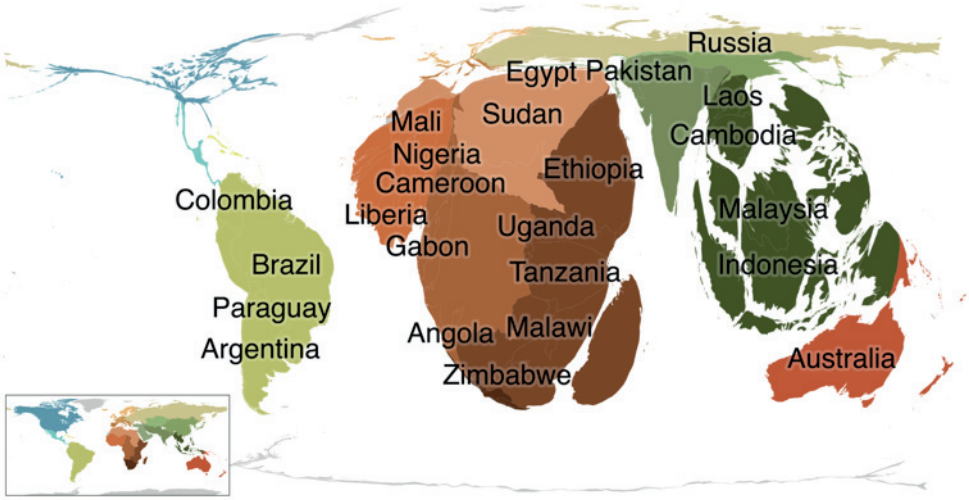

Figure 2. Cartogram (distorted map) where each country's size has been re-scaled to represent the total amount of acquired land: the more land acquired, the larger the country size in the map. Countries where more than 100,000 hectares of land is contracted are labelled with country name, and countries are coloured by sub-region. Data from Grain (2012) and Land Matrix (2014).

The low proportion of land deals in production can partly be explained by financial land speculations by private firms, who hope to gain financial benefits from the increased food- and energy-driven demand for agricultural land (Kugelman & Levenstein 2012). Another reason is that many investments have failed at the implementation stage, resulting in either abandonment, or transfer to a new investor (Cotula, 2013). This has especially been the case for land acquisitions related to biofuel production from crops like sugarcane and jatropha (Ahmed et al. 2017; Borras et al. 2010; Hashim 2014; Sanderson 2009).

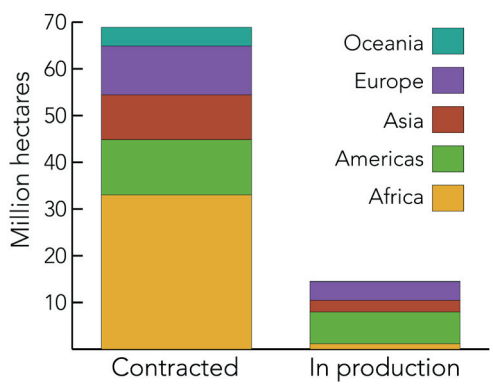

Figure 3. Total area of land acquisitions in the world, grouped by continent. The graph shows the difference in contracted land leases, and acquired land currently in agricultural production. Data from Land Matrix (2017).

The global scope of large-scale land acquisitions led to the development of *Paper I*, in order to understand how countries and land systems are connected to each other through virtual trade of land and water resources. *Paper II* focus on Africa as a whole, since it is the continent where most land has been contracted. Tanzania was selected in order to investigate what effects the global and continental patterns of land- and water-use changes have in selected areas subject to large-scale land acquisitions (*Paper III & IV*).

The case of Kilombero Valley, Tanzania

Tanzania is one of the highly targeted countries for land in East Africa, where in total about 256 000 ha of land has been acquired (of which approximately 14% is in production according to Land Matrix (2018)). I conducted my fieldwork in Kilombero Valley, located in the Kilombero and Ulanga Districts of southern Tanzania (Figure 4). The fieldwork site was selected in collaboration with a Tanzanian NGO working on land right issues, with the motivation that it is one of the areas experiencing rapid socio-environmental change due to large-scale land acquisitions. However, a range of further factors makes it an ideal place for this study. The Kilombero Valley is a biodiversity hotspot and has one of the largest freshwater wetlands in East Africa (Kangalawe & Liwenga 2005b). It is referred to as the bread basket of East Africa due to its perfect conditions for agriculture with year-round warm temperatures, fertile soils, and abundance of water (Mombo 2011). Most people (76%) live in rural areas and primarily engage in food production through small-scale farming, fishing and pastoralism. These livelihoods closely connect people to the environment, and make them particularly vulnerable to environmental change (Kangalawe & Liwenga 2005a). The area is experiencing rapid population growth. Between 2002 and 2012 the rural population grew by 24%, from 230,774 to 304,241 (NBS 2016). Population growth is not only an effect of high birth rates, but also due to rapid migration to the area, particularly by the influx of Masaai, Sukuma, and Barbaig pastoralist groups, who are leaving other parts of Tanzania due to land degradation, or land investors forcing them to find land elsewhere (Nindi et al. 2014).

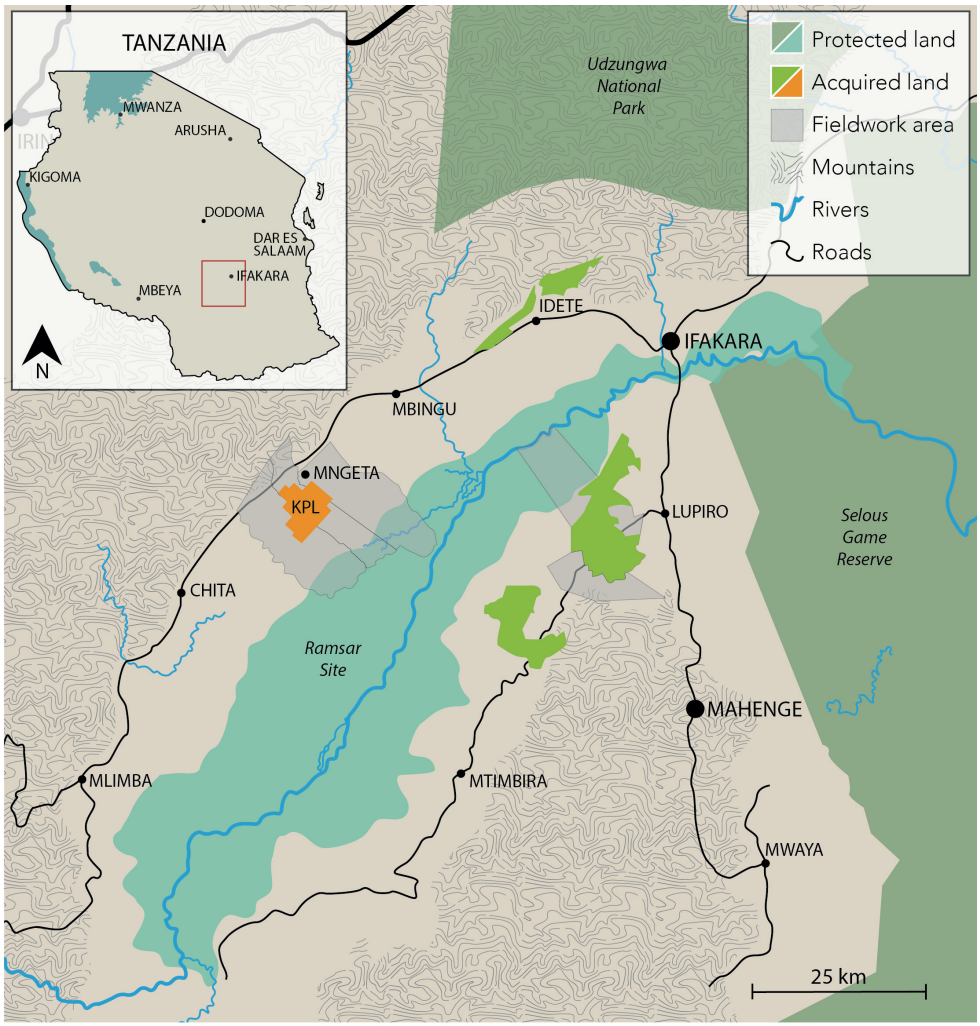

Figure 4. Map of study area for fieldwork. Dark green and turquoise land is protected by global or national initiatives, while light green and orange areas indicate areas for large-scale land acquisitions in the Valley. The light grey area delineates the village land of the case study areas.

There are many actors engaged in land- and natural resource management of the Kilombero Valley, mainly for conservation or agricultural purposes. These actors range from individuals (e.g. farmers), local NGOs (e.g. Kilombero Valley Development Organization, KIVEDO), domestic agribusinesses (e.g. ILLOVO), transnational agribusinesses (e.g. Kilombero Plantations Limited, Kilombero Valley Teak Company), and global conservation initiatives (e.g. Ramsar). The area became increasingly attractive for foreign agribusinesses since the national initiative Southern Agricultural Growth Corridor of Tanzania, SAGCOT, was launched in 2011.

SAGCOT coordinates agribusiness partnership between the Government of Tanzania, private companies, and international donors, and aims to mobilize 3 billion USD in investments, bring 350,000 hectares of land into commercial farming, create 420,000 new jobs, and lift 2 million people out of poverty (Scherr 2013). Conservation initiatives are based on global interests to protect the wetland area, which was declared as a Ramsar site in 2006, and is thereby protected under the Convention on Wetlands of International Importance (Ramsar 2016). There are also national initiatives to protect biodiversity with extensive areas of national parks and forest reserves (e.g. Selous Game Reserve, and Udzungwa National Park).

I conducted fieldwork in two areas in Kilombero Valley where large-scale land acquisitions have been in operation over an extensive period of time (highlighted in grey in Figure 4). This made it possible to explore socio-environmental change in relation to land use and land cover changes that have occurred since land was acquired in the two areas. The two areas of focus are affected by large-scale land use changes by Kilombero Plantations Limited, growing rice on 5,800 ha of land for non-local markets since 2007, and Kilombero Valley Teak Company, growing teak on 28,132 ha of land for export since 1992. Figure 5 gives a glimpse of the study area, and shows some of the main drivers of socio-environmental change in the region.

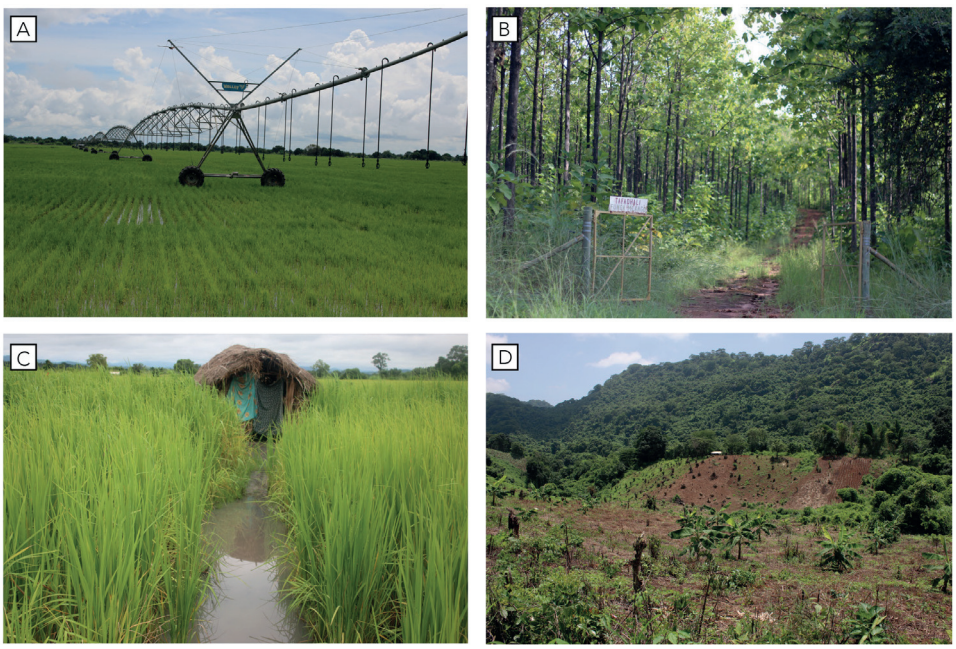

Figure 5. A) Rice fields of Kilombero Plantations Limited are managed with sprinkler irrigation systems with water extracted from one of the rivers that feed the wetland area with freshwater. B) Teak plantation of Kilombero Valley Teak Company, fences disturb the migration of wildlife in the area. C) Farmland expansion by local small-scale farmers to the protected Ramsar wetland area. D) Farmland expansion by small-scale farmers to the protected mountain forest. Also charcoal production is a reason for deforestation.

Data and methods

I have applied different research approaches in the four papers of this dissertation, spanning global, continental, and local scales (Figure 6). On the global to continental scale, I use available data for large-scale land acquisitions in order to quantify environmental change with a focus on land and water (*Paper I & II*). The purpose is to generate an understanding of the relational patterns that emerge, and what implications these patterns might have on people and the environment on a national, and sub-national level. At the local scale, I combine qualitative and quantitative methods in order to understand people's perceptions of socio-environmental change (*Paper III*), and compare these with satellite image observations (*Paper IV*).

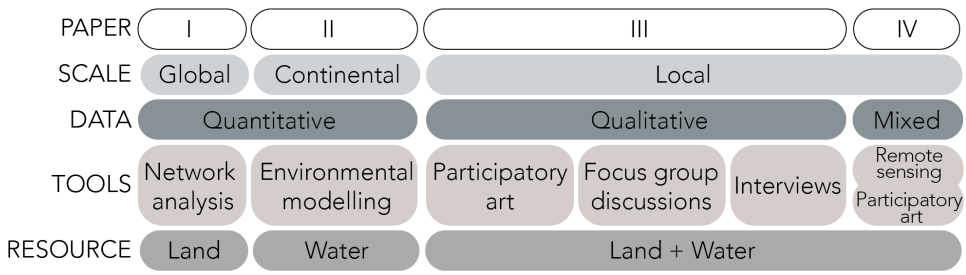

Figure 6. Overview of the different research approaches in the four papers of this dissertation.

Paper I: Network analysis of global patterns

Paper I was developed in order to investigate the spatial and relational pattern that has emerged between countries that engage in large-scale land acquisitions. This is one of the first attempts of analysing global land acquisitions as a telecoupled system.

Global datasets of large-scale land acquisitions

The network analysis is based on data from two online databases: Grain (2012) and Land Matrix (2014). Grain (www.grain.org) is an international non-profit

organization, and the first to provide a large dataset about land acquisitions. The database has, however, not been updated since it was first uploaded to the Grain website. Land Matrix is an independent global initiative to monitor large-scale land acquisitions, and the data is continuously updated and freely available online at www.landmatrix.org. The databases include information about:

- Investor name.
- Origin of investor (one or many countries).
- Where land is acquired (on a local or national level).
- How much land is contracted, and how much land is currently in operation.
- What crops are grown (or planned to be grown).

The global datasets from Grain and Land Matrix were merged and edited (e.g. duplicates were removed) to obtain the full extent of the global pattern of land acquisitions. The data were re-shaped into a format that enabled network analysis.

Network analysis

Network analysis is a method for observing and analysing the patterns and connectivity of a system (Newman 2010), and has good potential for operationalizing the telecoupling framework (Liu et al. 2016), but the research is still in its infancy. In this dissertation, a network approach was chosen in order to investigate the relational connections between countries that participate in global land trade through large-scale land acquisitions. The land acquisition network was created with the open access software Gephi (Bastian et al. 2009), which provided a platform to visualize the network geographically. The software package UCINET was also used for some of the analyses (Borgatti et al. 2002).

As illustrated in Figure 7, the basic building blocks of networks are nodes and links (represented as circles and lines). In *Paper I*, the nodes represent countries that participate in the global land acquisition network, either as "importers" (represented by the investor's country of origin) or "exporters" (i.e. countries where land is acquired) of land. Links appear if there is a connection between two countries, in this case represented by a virtual trade of land, and a shift in land ownership.

The statistics provided by network analysis are local and global, in this context meaning that a measure can say something about a specific node (local), or the node's role in the network as a whole (global). Degree centrality (a local measure) and betweenness centrality (a global measure) are two centrality measures that have been used to identify key players in the land acquisition system, and the role of countries for providing network connectivity. These measures and network statistics can be used to understand how risks and vulnerabilities may propagate throughout the network.

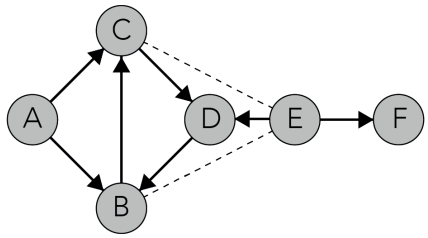

Figure 7. Conceptual model to explain network features and metrics used in Paper I. The figure shows a directed network with six nodes and seven links. Dashed lines are added in order to explain how the local clustering coefficient is calculated.

Degree centrality is a local network measure that have been used to describe the number of land trade partners associated with a country, as it represents the number of links connected to a specific node (Figure 7, A = 2, D = 3, E =2). If a network is directed, each link has a direction to or from a node, which gives each node a certain in- or out-degree (Figure 7, $D_{in\text{-}degree} = 2$, and $D_{out\text{-}degree} = 1$).

Betweenness centrality is a global network measure that describes how often a node appears on the shortest path between all other nodes in the network (Figure 7, $D_{undirected} = 6$ times: A-E, A-F, B-E, B-F, C-E, C-F, and $D_{directed} = 3$ times: E-B, C-B, E-C). It can therefore be used to understand the importance of nodes for providing network connectivity, as nodes with high betweenness centrality act as a bridge between many other nodes in the network. Hence, if a node with high betweenness centrality is removed from the network (e.g. acquired countries banning land acquisitions, acquiring countries withdrawing from investments, temporary export bans, harvest losses due to extreme weather events) it will affect many other nodes in the network, as well as their connectivity. In *Paper I*, the measure is normalized by dividing each node's betweenness centrality by the total number node pairs in the network, which produces a value between 0 (0%) and 1 (100%). A value near 1 indicates a central player in the network, and a value near 0 means that a node is peripheral and rather uninfluential.

The local clustering coefficient has been used to describe the tendency for countries to form tight groups, which depends on how well connected a given node is to its neighbours, and in turn how well the neighbours are connected to each other. The clustering coefficient is calculated as the ratio of how many partners are linked to a node, in relation to the theoretical maximum of land trades that could occur between those linked partners. For example, in Figure 7, D is linked to three partners (B, C, E). The nodes B, C, and E could be tied to each other with three links (indicated with dashed lines), but there is only one other link between B and C, the local clustering coefficient of D is therefore calculated as 1/3 = 0.33 (or 33%). In *Paper I*,

the local clustering coefficient was used to identify land trade submarkets, representing groups of countries with tight land trading relationships.

Finally, the average nearest neighbour degree can be used to indicate the likelihood that nodes are connected to other nodes of similar degree (assortative relationship), or dissimilar degree (dissassortative relationship). In *Paper I*, this measure was used in order to understand if countries with many (or few) trading partners tend to engage with countries with similar (i.e. assortative trade orientation) or dissimilar (i.e. dissassortative trading orientation) number of trading partners. For this measure, the direction of trade (import or export) was also taken into consideration, which makes it is possible to gain general insights regarding country-level factors that may lie behind any observed asymmetries of trade relationships.

Paper II: Modelling water demand for land acquisitions in Africa

Paper II was developed in order to add the element of freshwater to the understanding of socio-environmental change, since changes in land use are also accompanied with changes in water resources, which in turn might lead to conflicts between water users.

Data for modelling blue and green water requirements

For the continental-scale analysis, focus was on land acquisitions in operation in Africa. The sub-national coordinates[1] of data from Land Matrix allowed for modelling and mapping place-specific green and blue water requirements for crops in production based on local climate data (approximately 55 km in resolution), as opposed to aggregated country-level data. Focussing on land acquisitions in production also made it possible to crosscheck the data with satellite imagery from Google Earth.

When accounting for water requirements of agricultural products, it is important to distinguish the type of freshwater that is appropriated. This can facilitate an understanding of what type of water is used (i.e. if water is from green or blue water sources), and point to trade-offs between human water use and ecosystems needs. Green water is the water that is available to crops as soil moisture from precipitation. Blue water is the above or below ground water in e.g. rivers, dams, and groundwater (Falkenmark et al. 2004). For irrigated agriculture, the soil moisture is enhanced with

[1] Sub-national coordinates for each land deal were obtained through personal communication with Matthias Brück, 24/7 2014, at the time developing the Land Matrix webpage.

freshwater from blue water sources, and the blue water use of crops therefore varies depending on the water use efficiency of the irrigation system.

Agro-ecological and hydrological modelling

Blue and green water demand was estimated using the dynamic agro-ecological and hydrological model Lund-Potsdam-Jena Managed Land (LPJmL), as it enables site-specific simulation of crop production, and blue and green water use for different irrigation scenarios. Agro-ecological and hydrological modelling made it possible to estimate a range of water requirements for different irrigation scenarios, which is essential since there is little information about irrigation systems on acquired land (Chiarelli et al. 2016). Modelling also made it possible to compare water requirements of crops grown on acquired land, to a baseline scenario of traditional crops.

LPJmL uses gridded (0.5 degrees resolution, approximately 55 km) monthly climate inputs (temperature, cloudiness, rainy days and precipitation from CRU 3.10), soil textures, and global atmospheric CO_2-concentrations to model hydrological variables, phenology, agricultural outputs, and the carbon cycle. LPJmL has a detailed hydrology module, with a river routing and irrigation scheme (Rost et al. 2008), management of dams and reservoirs (Biemans et al. 2011), and a five soil-layer hydrology (Schaphoff et al. 2013). LPJmL's hydrological scheme, including the simulation surface and subsurface runoff, soil evaporation, plant transpiration, infiltration and percolation, has been demonstrated in numerous studies and validation efforts (Elliott et al. 2014; Fader et al. 2016).

The extended version of LPJmL from Fader et al. (2015) represents 26 crops or groups of crops: 13 annual crops, two bioenergy crops, 7 agricultural trees and shrubs, and three other categories (vegetables, fodder grasses and managed grasslands). Most of the crops in production on acquired land in Africa are included in LPJmL, but some, including acacia, cacao, castor oil plant, coffee, flowers, jatropha, oil palm, pongamia pinnata (a legume tree for biodiesel production), rubber, sesame, tea, teak and teff were represented through the class "managed grasslands", which was parameterized as a mixture of C3 and C4 grass and gives an estimate for the behaviour of these crops.

Paper III: Local perceptions of socio-environmental change

For *Paper III*, it was crucial to understand how people that are affected by large-scale land acquisitions experience land system change, and what changes they observe. With the aim to co-produce knowledge, the research focus and questions were

developed during fieldwork in Kilombero Valley, Tanzania, by combining established qualitative methods (focus group discussions, interviews, narrative walks, field observations), with novel participatory art workshops inspired by ethnography and participatory research (Chambers 1994).

Focus group discussions, interviews, narrative walks, and field observations

Firstly, I arranged focus group discussions with farmers, fishermen, and pastoralists in order to get an overview of local experiences, observations, and opinions of socio-environmental change in communities that lease land to large-scale agribusinesses. The aim of a focus group discussion is to obtain data from a purposively-selected group of people, rather than from a statistically representative sample of the broader population, and thereby gain in-depth understanding of issues, since the group dynamic can help participants to explore and clarify their views (Kitzinger 1994; O Nyumba et al. 2018). I consciously decided to include people who are highly dependent on natural resources in the communities where land is being leased, and therefore vulnerable to land system changes.

Questions were developed with the overarching aim to understand past, present, and future changes in natural resources, and natural resource use. The discussions were open ended, in order to illuminate what socio-environmental changes and challenges are most important for the participants (Figure 8). Questions were related to what natural resources are important in the area, how people use them, and what benefits they obtain from those resources. From there, discussions focussed on if there have been any changes in natural resources, and what the participants think are the reasons for change. Thereafter, the discussion revolved around the future of the community and natural resource use, how the participants want natural resource use to change, and how to make change happen.

Spending time in the field also allowed me to arrange interviews with other key actors that influence natural resource management in the Kilombero and Ulanga Districts. This includes people working for the agribusinesses (Kilombero Plantations Ltd., Kilombero Valley Teak Company), district level authorities, the local Ramsar office staff, agricultural research institutes, local NGOs, and other sporadic encounters with people that live in the area. Interviews are useful when wanting to understand individual experiences, opinions, and values without interference from others (Kvale 2008). The interviews were based on the same questions as those posed in the focus group discussions in the villages, and helped me understand if, and how, the perceptions of natural resource managers overlap or diverge from the perceptions of the farmers, fishermen, and pastoralists.

Figure 8. Qualitative methods during fieldwork. A) Focus group discussions in one of the fieldwork communities. B) Interviews with a family that was re-settled to another area when the foreign agribussines acquired land.

Narrative walks, and field observations were conducted with people from the village who showed me different areas mentioned in the focus group discussions, such as the wetland, mountain forest, as well as new and old village and farmland areas (Figure 9). This enabled me to understand place-specific social and natural dimensions of the landscape, and additional local experiences of socio-environmental change (Fienup-Riordan et al. 2013; Jerneck & Olsson 2013).

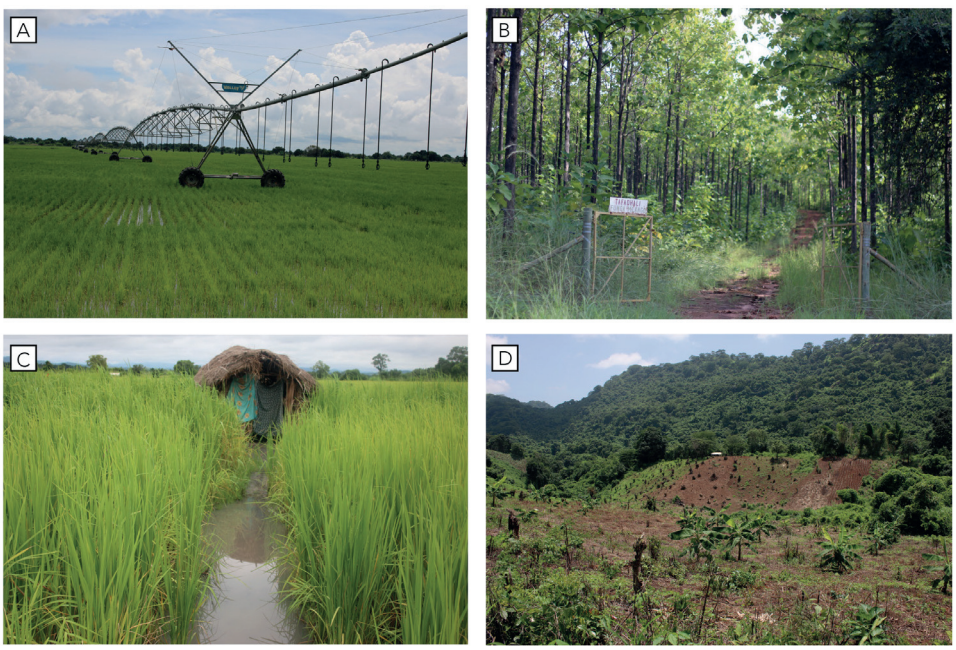

Figure 9. Qualitative methods during fieldwork. A) Field observations with farmers showing land that was previously small-scale farming and now has been converted to large-scale rice plantations. B) Field observations, observing the size of teak tree leaves. C) Field observations and narrative walks with a farmer that shows small-scale rice field expansion to the protected Ramsar area. D) Field observations and narrative walk with forest ranger that shows illegal charcoal production, and expansion of small-scale farming in the protected mountain forest.

Participatory art workshops

Participatory art was used as a means to engage local farmers, fishermen, and pastoralists in the co-production of knowledge about socio-environmental change. The narratives from the focus group discussions and interviews formed the foundation for two participatory art workshops, one held in the area close to the rice farm of Kilombero Plantations Ltd., and one close to the teak plantations of Kilombero Valley Teak Company. The village, natural resources, and natural resource use were depicted as paintings, representing the past, present and future (Figure 10). A Tanzanian artist, Joseph Mwalyombo, instructed the participants how to paint the Tanzanian art-style tinga-tinga, which often represents people and animals in different environments.

Figure 10. Participatory art workshop. A) Sketching the main features and locations of rivers, mountains, settlements, farmland. B) Instructing participants how to mix colors, make broad stroaks with the brush, and build the background of the painting. C) Adding details to the painting, a participant fills in color between the lines of what will visualize a modern house with concrete walls and tin roof. D) One of the participants add more layers to the painting, here adding tin and grass roofs to the houses.

Paper IV: Remote sensing and socio-environmental change

As there is a lack of historical quantitative data and maps of the Kilombero Valley, it is difficult to evaluate how experienced socio-environmental changes relate to actual changes in the environment. The lack of baseline data made me curious to explore if

local perceptions of change could be observed and analysed from space with remote sensing. I also wanted to make a land cover change detection based on local concerns and land cover categories developed in consultancy with people on the ground (i.e. forests, shrubland, grassland, wetland, farmland, and water).

Remote sensing and land cover classification

Satellite data were used to quantify land use and land cover changes for one of the fieldwork sites in Kilombero Valley, surrounding the area where the agribusiness KPL grow rice. Satellite images were collected from Landsat (Table 2) and analysed for two different years: 2004 and 2014, which represent the periods just before land was acquired, and the state of the area during approximate time of fieldwork (Figure 11).

Table 2. Information about the satellite images used in dissertation work.

Product ID	Acquisition date	Satellite	Instrument
LC81680662014194LGN00	2014-07-13	LANDSAT 8	OLI TIRS
LT51680662004199JSA00	2004-07-17	LANDSAT 5	TM

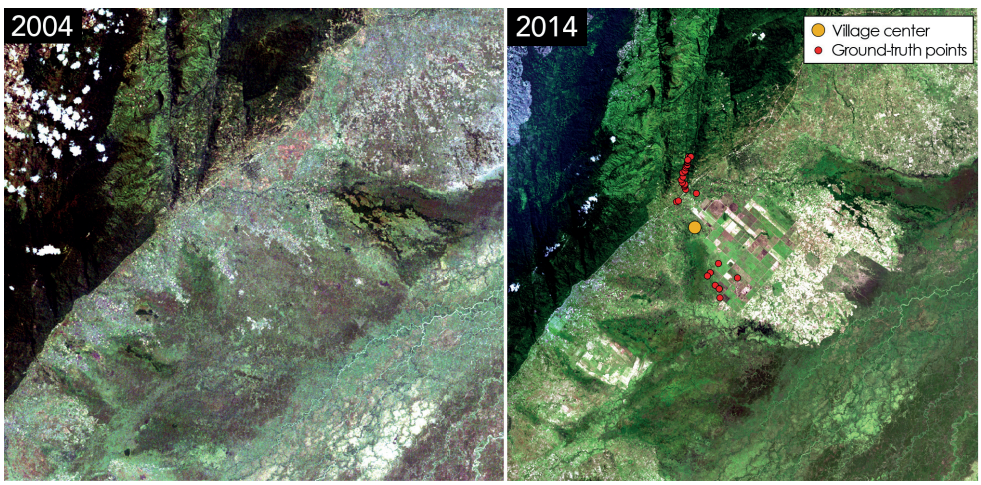

Figure 11. Satellite images used for supervised classification. The two time-slices (2004 and 2014) represent the time before the arrival of the agribussiness (Kilombero Plantations Limited), and the current state during fieldwork. The yellow dot represents where the participatory art workshop was held for Paper III, and the red dots show areas where the (36) ground-truth points were collected for classifying past and current land cover.

Landsat is of great value for land change detection since it is the longest continuously running program for capturing satellite images of the Earth's surface (Landsat 2018). The first satellite was launched in 1972, and since then eight different satellites with upgraded instruments have captured millions of satellite images. All images are freely available and can be viewed and downloaded through the U.S. Geological Survey

(USGS) "earth explorer" website. Each image is 185x185 km in spatial extent, and has a temporal resolution of 16 days. Landsat 8 is the most recent satellite in the Landsat program, and each image contains multiple spectral bands of non-visible and visible wavelengths ranging from 15 to 100 meters spatial resolution (Table 3).

Table 3. The 11 bands of Landsat 8 and their spectral and spatial resolution. The bands that are also recorded by Landsat 5 are highlighted in grey.

Band	Description	Wavelength (micrometers)	Resolution (meters)	Bands used in analysis in Paper IV
Band 1	Coastal Aerosol	0.43-0.45	30	
Band 2	Blue	0.45-0.51	30	x
Band 3	Green	0.53-0.59	30	x
Band 4	Red	0.64-0.67	30	x
Band 5	Near Infrared (NIR)	0.85-0.88	30	x
Band 6	SWIR 1	1.57-1.65	30	x
Band 7	SWIR 2	2.11-2.29	30	x
Band 8	Panchromatic	0.50-0.68	15	
Band 9	Cirrus	1.36-1.38	30	
Band 10	Thermal Infrared (TIRS) 1	10.60-11.19	100	
Band 11	Thermal Infrared (TIRS) 2	11.50-12.51	100	

In *Paper IV*, two satellite images were used to perform supervised land cover classifications of the study area for year 2004 and 2014, using six land cover categories established by participants during fieldwork (i.e. wetland, farmland, forest, grassland, water, shrubland).

A supervised classification means that the researcher specifies training sites (i.e. polygons that contain spectral signatures that represent a certain land cover class) in order to classify the whole image (Humboldt State University 2018; McCoy 2005). Ground truth points are normally collected in field in order to define training sites, but in this case the ground truth points were limited to 36 geo-referenced locations (locating areas that have changed, and remained the same, between 2004 and 2014), which is not sufficient for classification and validation. There are also no ground truth points for year 2004 since no fieldwork was done at that time. Therefore, training sites and 60 validation points for each class were identified in satellite images (Bagan et al. 2010), mainly from high-resolution imagery available through Google Earth (from year 2012 and 2013), as well as the Landsat images themselves by combining different spectral bands to distinguish between land cover classes. Both false-colour composites and vegetation indices were used to observe and distinguish different land cover classes in the Landsat images.

The combination of different spectral bands has facilitated global change research, particularly within the fields of agriculture, geology, forestry, and mapping (Landsat 2018). For example by analysing vegetation "greenness" by combining non-visible infrared bands, with visible green, and blue bands, which creates an image that for example enhances the presence of vegetation in different shades of red (Jackson et al.

2004). This type of false-colour composite was particularly valuable for delineating forests, shrubland, and farmland areas.

Another benefit of pixel-based spectral information is the possibility to create different indices for identifying and separating different land cover types. The Normalized Difference Vegetation Index (NDVI) is the difference between near-infrared (850 – 880 nm) and red (640 – 670 nm) surface reflectance divided by their sum, and captures the spectral signature of live green vegetation (Rouse et al. 1973). Normalized Difference Water Index (NDWI) is the difference between green (530 – 590 nm) and near infrared (850 – 880 nm) surface reflectance divided by their sum, and captures plant water content. NDVI and NDWI were used to distinguish between different types of vegetation and land cover classes, for example farmland and wetland pixels.

The land cover classification was performed in the open source software R, using the *RandomForest* (Liaw & Wiener 2002) and *Caret* (Kuhn 2008) packages, and further analysed in QGIS, an open source software for geographic information systems. The supervised classifications for the two time-slices were then compared to each other in a cross-tabulation in order investigate how the different land covers have changed over time. Thereafter, the quantified land cover changes were compared with perceptions of socio-environmental change described in *Paper III*.

Results and discussion

This chapter summarizes some of the main insights about socio-environmental drivers, impacts, and feedbacks in the context of large-scale land acquisitions that were obtained at the different scales of analysis. An initial overview is presented in Table 4, followed by summaries of, and discussions about, land system change for each paper. The final section adds some perspectives and reflections on scale and space, and different modes of knowledge production.

Table 4. Identified drivers, impacts, and feedbacks of socio-environmental change for the four papers of this dissertation.

Paper	Drivers	Impacts	Feedbacks
I	Country-to-country relations/connections (in this context investors are represented by their country of origin).	1) Countries susceptible to rapid and vast land cover changes. 2) Countries where there is a shift in land ownership. 3) The land acquisition network is vulnerable to shocks, since a few key actors act as hubs for either importing or exporting land.	1) The global trade of land might lead to conflicts over land and water resources. 2) Abrupt social (e.g. political, economic) or environmental (e.g. droughts, floods) changes in these key nodes would affect many other nodes in the network.
II	Large-scale land acquisitions in operation in Africa (mainly for forestry and biofuel purposes).	1) Crops grown on acquired land require more water than traditional crops. 2) Use of irrigation systems increase the use of water from blue water sources (e.g. rivers, dams, groundwater). 2) Crop choice has bigger incluence over total water use than the water-use efficiency of different irrigation systems.	1) High levels of blue water use might lead to conflicts over water. 3) It is not possible to analyse how changes in water use affect people on the ground at this scale and level of analysis.
III	1) Large-scale land acquisitions for rice, and teak production (KPL and KVTC). 2) Population growth. 3) Conservation areas.	1) Large-scale land acquisition expands on small-scale farmland and wetland. In turn, small-scale farmland shifts to, and expands over protected parts of the wetland and mountain forest. 2) Large-scale land acquisition expands over highland forests, replacing natural forests with teak. Also here, small-scale farming expanded towards the protected wetland due to population growth.	1) Deforestation - drying out of rivers - decrease in fish stocks. 2) Use of fertilization and pesticides - lower water quality - negative health impacts. 3) lower land availability - intensified agriculture - lower soil fertility - lower agricultural yields. 4) expansion of small-scale farming + influx of pastoraist groups - negative effects on wildlife and biodiversity.
IV	1) Large-scale land acquisition for rice production (KPL). 2) Population growth.	1) Alignment in exerienced and quantified change regarding farmland expansion to the wetland. 2) Divergence between local perceptions of deforestation and quantified changes in forest cover.	1) It is not possible to analyse socio-environmental feedacks with the remote sensing approach in isolation, feedbacks are obtained from Paper III.

Paper I: Land acquisitions as a telecoupled system

Paper I aimed to investigate the geographical pattern and distant relationships between countries that engage in large-scale land acquisitions, and analyse land acquisitions as a telecoupled system. We found that 126 countries participate in the land trade network, but only a few of these account for the majority of land acquisitions (i.e. they have a high degree centrality) and play a disproportionately central role in providing network connectivity; the main importers of land are China, the US, and the UK, and the main exporters of land are Ethiopia, Philippines, and Madagascar.

Three countries, China, the US, and the UK, have high normalized betweenness centrality values, with the shortest trading path between any two countries traversing one of these countries over a third of the time. These three countries are therefore particularly important for providing network connectivity, as these hubs act as a bridge between many other countries in the network. This uneven network structure is prone to propagate risks, as many other countries become vulnerable to political, economic, and environmental changes in these key countries (Barabasi 2002). The local clustering coefficient was used to identify land trade submarkets in the global land-acquisition network, representing countries with tight land trading relationships. High clustering could provide a buffer against global geopolitical and environmental disturbances since countries with high clustering coefficients might be less dependent on global land trade. Overall, the land trade network displayed a low incidence of clustering, except a few distinct submarkets like Finland, Sudan and China, or Swaziland, the UK, and South Africa. The clustering coefficient could be explored further in order to analyse if land-trade relations are shaped by pre-established historical, political, and colonial ties. The average nearest neighbour degree indicates that the land trade network is slightly dissassortative, meaning that countries with a low number of export partners tend to trade land with countries with a high number of import partners, and vice versa. For example, Cameroon exports land to six countries, which in turn import land from 17.8 countries on average. The dissassortative pattern of the global network implies that low-income countries tend to have many export partnerships with high-income countries, but import little land themselves.

Network theory made it possible to understand land acquisitions as a telecoupled system (Friis et al. 2015), where distant places are connected and affect each other in terms of resource use, risks, and vulnerability. Research at the country-level of analysis can indicate how the structure of the network is prone to propagate socio-environmental risks and vulnerability for both importers and exporters of land. For example if there are crop failures due to extreme weather events like droughts and floods, countries that acquire land are likely to also be affected by these distant

environmental changes. This is highly relevant since droughts and floods are expected to occur more often in the future due to effects on temperature and precipitation from climate change (IPCC 2014; Kotir 2011). There are also risks that countries where land is acquired will end up with unsatisfactory infrastructure development and job opportunities if investors stop production due to global market changes, which has partly been seen in the global biofuel market (Ahmed et al. 2017).

Paper II: Land acquisitions and water conflicts

Paper II was developed in order to investigate risks of water scarcity and conflicts in areas of large-scale land acquisitions in Africa. The continental-scale analysis made it possible to add details about water requirements on a sub-national level, while still being able to map large-scale patterns of hydrologic change (Figure 12). *Paper II* reveals that crops grown on acquired land require more water than traditional food crops, and that blue water demand mainly depends on crop type, and irrigation efficiency (as opposed to climate, which determines green water demand). The type of crops grown on acquired land is therefore a dominant driver of change in water use. The ratio between blue and green water demand for each land acquisition in production highlights 'blue water hotspots', which we define as areas where more than half of the total water demand needs to be extracted from blue water sources to obtain maximum yields. We found that 29-53 out of 134 land acquisitions are blue water hotspots, depending on the irrigation efficiency of the land acquisition. Even with the most water efficient irrigation system, 18% of the land acquisitions would still be blue water hotspots and considered as high-risk areas for water conflicts.

Linking back to the concept of telecoupling, the hotspot areas can be used to analyse how sub-national water budgets change due to distant demands of agricultural products. The hotspots can also be used to identify areas of socio-environmental change, where people and the environment might face severe water-related challenges due to increased pressures on water resources.

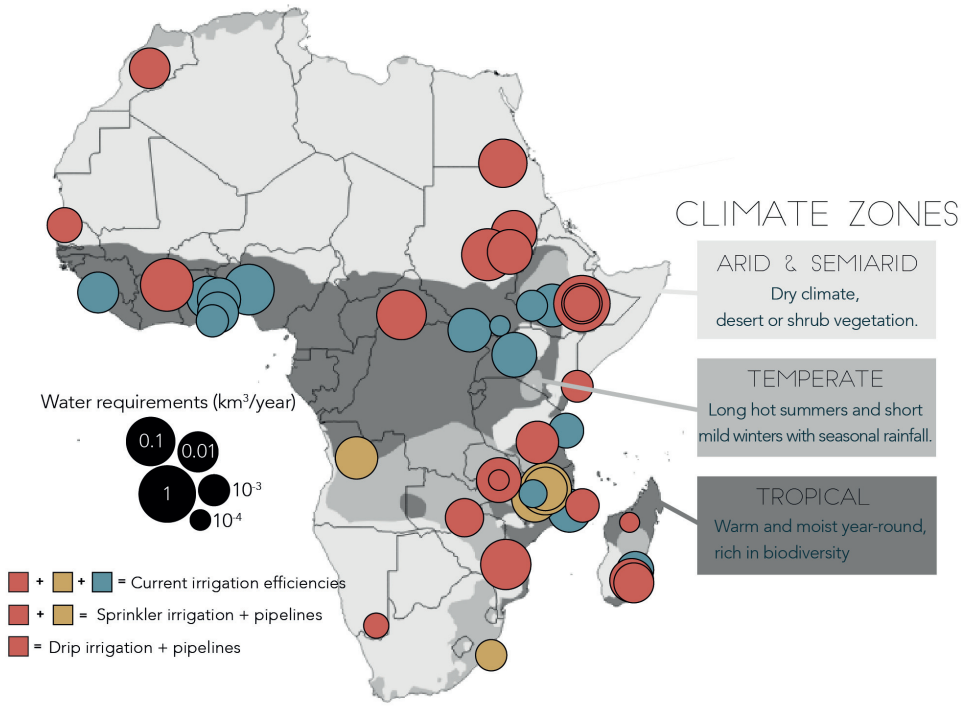

Figure 12. Blue water hotspots for land acquisitions (in operation) in Africa. The map shows land acquisitions where more than half of the water needs to be extracted from blue water sources in order to obtain maximum yields. The blue water extractions depend on the efficiency of the irrigation system, here represented by the color of the dots (pink, yellow, blue). The size of the dots represents the total water requirement of crops grown. The map shows that blue water hotspots appear in all types of climate zones, which indicates that the crop type is the dominant driver of water use, since blue water hotspots also appear in water rich areas.

Paper III: Socio-environmental drivers, impacts, and feedbacks

Paper III is a concrete example of how effects of the telecoupled land acquisition system are experienced on the ground, as well as how land system change contributes to changes at other nearby sites, using Kilombero Valley in Tanzania as the study site. As such, it is the only paper in this dissertation that manages to fully capture the complex interaction between socio-environmental drivers, impacts, and feedbacks. The dominant narratives of socio-environmental change point to large-scale transformation and expansion of farmland (both from the establishments of foreign agribusinesses, as well as expansion of small-scale farms) towards the protected wetland and forest. The rapid farmland expansion is partly due to that the two agribusinesses have not offered any substantial options for employment, and local

farmers remain in poverty and need to continue small-scale farming on more marginal land. Other observed environmental changes relate to rivers that dry out completely during dry seasons, as opposed to in the past when there was an annual flow. Lower water levels (explained as a consequence of irrigation and planting of water demanding trees like teak), coupled with overfishing has led to a reduced amount of fish in the rivers, and more difficult conditions for fishermen. Participants also report that the wildlife, in particular elephants, has disappeared from the area. They trace this change to disturbances in the landscape caused by large-scale farms, as well as rapid increase of pastoralists and cattle to the area.

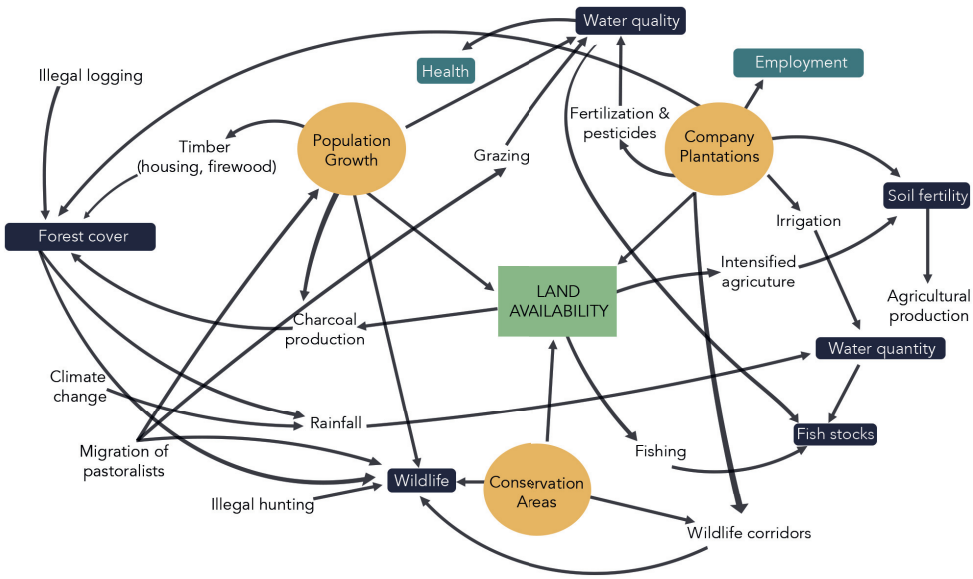

Figure 13. Causal loop diagram that represents the main drivers, impacts, and feedbacks of socio-environmental change in Kilombero Valley.

Key findings indicate that there are multiple drivers of socio-environmental change in Kilombero Valley that are internal (e.g. population growth) and external (e.g. large-scale land acquisitions, conservation areas). To fully understand socio-environmental impacts of land use and land cover change, researchers cannot only look at land acquisitions in isolation, but also need to include effects from population growth, migration patterns, initiatives for nature conservation, and infrastructure development projects, since they all play a big role in land system change, and natural resource use.

The participatory painting process added value to the research process as a whole, as it created a natural platform to stay in the fieldwork area for a longer time (8 weeks in total) and get familiar with people and the environment, as well as to give the participants a sense of ownership over their contribution to research. This is

important since many researchers make very short field visits (e.g. a few hours, or a day), extract information, and rarely report back to the community how their information was used. In this case, I re-visited the villages in 2016 in order to disseminate copies of the paintings, to share the article, and to invite village leaders to participate in an exhibition of the paintings at the National Museum and House of Culture in Dar-Es Salaam.

Paper IV: Mixed approaches to study socio-environmental change

Paper IV shows that qualitative and quantitative research approaches can be combined in order to explore drivers, impacts, and feedbacks of socio-environmental change. Fusing two different research approaches can reveal aligning and diverging perspectives on environmental change. For example, alignment was found in perceptions and mapping of large-scale and small-scale farmland expansion towards the wetland. There was however divergence in the outcomes about farmland expansion to the mountain forest area, where local perceptions of rapid deforestation could not be corroborated with remote sensing techniques. Similar mismatches have been identified by other researchers (Fairhead & Leach 1995; Wainwright et al. 2013), who discuss that there are persistent discourses in e.g. science, education, and policy making, that claim that indigenous land use practices (e.g. slash-and-burn) create environmental crises like deforestation (King 2014). Fairhead and Leach (1995) however claim that these discourses are rooted in a misrepresentation of the actual drivers of socio-environmental change, which in turn have led to flawed development policies in the Global South. The researchers therefore stress the need for multiple methods for a deeper understanding of drivers, impacts, and feedbacks of socio-environmental change.

By adding remote sensing and land cover classification to the local perceptions of change, it is possible to understand convergence and divergence of results, and discuss strengths and limitations of what can be known by using different research approaches. In the case of Kilombero Valley, occurrence of rapid deforestation might not have been identified if only using remote sensing analysis, due to difficulties to see understory clearings, failure to classify forests and shrubland correctly, or mismatches in scale of analysis and interpretation. However, local perceptions of rapid deforestation might also be based on skewed memories of the past, persisting discourses of destructive indigenous land use practices and deforestation (as mentioned in Fairhead and Leach (1995)). This is something that needs to be investigated further in order to better support decision-making in the region. In the two proceeding sections, I add some perspectives on challenges that emerged from

using different scales of analysis, and highlight the importance to reflect on how social (e.g. economic and political) processes can construct and manipulate knowledge about space, nature, and scales when wanting to understand and describe socio-environmental change.

Reflections on scale and space

Scale is important for observing and explaining socio-environmental change, and is deeply embedded in land system science. According to Verburg et al. (2015) "Land system changes are the direct result of human decision making at multiple scales ranging from local land owners decisions to national scale land use planning and global trade agreements" (p. 4). The spatial scale of analysis, and choice of actors of a system, determines what type of socio-economic or environmental processes that can be identified. It is therefore important to acknowledge that scales construct certain kinds of relationships and knowledge (Manson 2008). In this dissertation, I use scale as different analytical entry points, and reflect on *what can be known* at the various scales of analysis, considering trade-offs between realism, precision, and generality (Chowdhury 2013; Levins 1966). Overall, there is an inverted relationship between generality and precision (e.g. global scale analysis tend to be general, local scales tend to be detailed and nuanced), which has motivated me to continuously shift scales of analysis. The limitations of each research approach opened up for new research questions, which led to the development of the papers in this dissertation in their specific order, which is presented in the following paragraph.

Paper I is global in its scope, analysing large-scale land acquisitions at the country-level. Aggregating individual land deals to the country level, however, limits the level of detail of system components, as it masks information about investors, crops planted, purpose of production, and how much land is in production. Nonetheless, the relational and geographical pattern can point to actors and areas of interest, where it is important to zoom in and add more layers of complexity (e.g. groups of countries that have strong ties, or geographical regions with many land acquisitions). By scaling down the analysis from the global to continental scale in *Paper II*, it was possible to add layers of detail to the data analysis of site-specific blue and green water requirements, while still being able to map continental-scale changes on a sub-national level for each individual deal. This study did not include any demographic data (e.g. population, income, livelihood) when defining blue water hotspots, which renders the high-risk areas of conflict somewhat hypothetical. Understanding actual experiences of socio-environmental change in relation to water use would provide an important foundation for understanding what kind of water-related challenges that are important for people in place (e.g. is it all about quantity, or is quality and accessibility of bigger importance?), which requires ground-based fieldwork. The need

to explore local experiences of socio-environmental change led to the development of *Paper III*, which provides a detailed understanding of local experiences, observations, and opinions. Fieldwork allowed for examining societal and environmental complexities and interactions with people in place, for example by identifying direct, and indirect socio-environmental impacts and feedbacks caused by local and non-local drivers, like farmland expansion of agribusinesses, as well as shifts, and expansions of farmland by small-scale farmers. *Paper IV* also operates at the local scale, and adds a quantitative estimate of change in land cover categories established by people in field. This paper is however more focussed on knowledge production (which will be discussed in the next section). Even though many land acquisition areas seem to experience similar socio-environmental effects (D'Odorico et al. 2017), the local impacts and feedbacks are site-specific and cannot be directly generalized to the continental or global scale. It is however possible to identify general socio-environmental trends by drawing on similarities between multiple case studies.

The following paragraphs add some reflections on specific challenges that emerged from using spatial scales as an entry point to observe and analyse large-scale land acquisitions. A first challenge was to find an appropriate level of representation for the actors that have increasing influence on land systems through large-scale land acquisitions, as investors range from individuals, multi-national corporations, banks, and governments (and therefore have a wide range in spatial representation). Some of these actors currently have more economic power than nations, as the 10 biggest corporations (topped by Walmart) are wealthier than all countries in the world combined (Global Justice Now 2016). As these somewhat spatially untied actors have direct and indirect impacts on specific spaces and places, it is increasingly important to address for how these powerful economic actors, their activities, and accompanied flows across sites are embedded within land system change, as how this embeddedness challenges the notion of space and spatial relationships (Munroe et al. 2014). In *Paper I*, the challenge was to represent two different types of actors/entities of the land acquisition system: one that represent spatially wide-ranging multinational firms and businesses (although the investors have a country, or multiple countries, of origin), and one that represents the geographical locations where land is acquired and the direct impacts of land system change are experienced. The network approach however made it possible to de-construct and re-construct the notion of space from spatial to relational, which is particularly useful when a given object is simultaneously local, regional, or global in terms of its connections to other phenomena (Bergmann & O'Sullivan 2018; Manson 2008). The critique of space also questions one of the core laws in geography, that "everything is related to everything else, but near things are more related than distant things" (Tobler 1970). The shift from geographical space to relational space highlights that relationships between countries are likely to be an effect of historical, colonial, linguistic, and political ties (though this was difficult to demonstrate with the clustering coefficient), rather than geographical space, which

has also been highlighted by Schoeman (2011). For example, Swedish investment in Tanzania are likely to be related to existing relationships built on a long history of aid and cooperation (McGillivray et al. 2016). Likewise, Belgian investments in the Democratic Republic of Congo are likely to relate to linguistic and colonial ties. This implies that classical geographical definitions of spatial extent, resolution, and Tobler's first law, may not be as important for understanding drivers, impacts and feedbacks of large-scale land acquisitions as the socio-economic relationships between actors and places. Similar discussions about reformulating proximities in Cartesian space to similarities in relational space have been outlined in (Bergmann & O'Sullivan 2018).

Another persistent challenge when writing this dissertation has been to distinguish between drivers, impacts and feedbacks of socio-environmental change. For example when developing the causal loop diagram in *Paper III* (Figure 13), it was difficult to distinguish what is a driver and what is an impact, since it depends on the scale of analytical entry. This was particularly the case for describing processes of deforestation, which is directly driven by people engaged in small-scale farming (who expand their farmland to forested areas due to increasing pressures on land), and charcoal production (which is an illegal activity, yet has a high demand and big market in Tanzania). The local drivers of deforestation are however an outcome (or impact) of larger global economic structures and actions that manifest themselves as large-scale land leases to powerful foreign agribusinesses, which in turn pushes small-scale farmers (economically less powerful people) to protected land areas due to the lack of alternative livelihoods. So, instead of thinking about the local as site specific, and the global as a separate site of generality, it is important to acknowledge that the global is embedded in the local (Munroe et al. 2014), and that local drivers of change are an outcome of a globally unjust economic system.

Reflections on knowledge production

In this section, I want to add some perspectives on knowledge-production in the context of large-scale land acquisitions, and how knowledge can be co-produced in order to integrate science and society to facilitate the development of sustainable land use practices. Participation of people outside of academia can help the researcher to develop research questions that are of actual concern for society, which in turn is important for bridging science and society for sustainable policy development and future decision-making.

The four papers of this dissertation were developed through an iterative process of gaining knowledge in fieldwork, while also exploring and analysing large datasets. The constant engagement with qualitative and quantitative research approaches led to

reflections about how knowledge is produced, using a top-down research approach (i.e. developing the research based on a pre-determined interest in a specific area of focus), as opposed to a bottom-up approach (i.e. developing the research based on local knowledge and concerns). For example, the local concerns about farmland expansion to the wetland and forest that were outlined in *Paper III* became a key focus of analysis *Paper IV*. Just as the concepts of scales and space can be discussed as social constructs (Manson 2008), so can the production of knowledge (Haraway 1989), meaning that all knowledge and understanding is subjective and situated, and connected to where, how, and by whom it is produced. All research methods therefore offer different opportunities for interpretation, understanding, and representation of 'reality' (Nightingale 2016). By applying different research approaches it is possible to provide different pieces of the puzzle and help build a clearer picture of drivers, impacts, and feedbacks of socio-environmental change.

Paper II is a good example of how a top-down approach can be useful for focussing on a specific socio-environmental challenge (i.e. increased blue water extractions and conflicts) but fails to link the observed changes to actual water-related challenges on the ground. Actual challenges might not only be linked to changes in water quantity, but rather to issues of water quality and accessibility, which can only be known through bottom-up approaches and engagement with people in the field. Even so, actual challenges on the ground might not even be related to water. The following example from Egypt highlights the need for local knowledge when discussing water conflicts and blue water hotspots (see Figure 14). In the middle of the desert, an investor is growing wheat, alfalfa, and potato with centre pivot irrigation systems (circular fields in the middle image). Satellite images show that water is provided from Lake Nasser, which is connected to the Nile (image to the right). The satellite image to the left in Figure 14 shows that no people lived in this area before, so it is not likely that the land acquisition has produced any local conflicts over water in this case. Blue water extractions might however impact people and ecosystems downstream, which highlight the need to observe and evaluate real socio-environmental and hydrological changes, impacts, and feedbacks at local to regional scales.

In the case of Kilombero Valley, decisions by non-local actors affect the local population who have little power to control the changes in the environment. Participatory research is a bottom-up approach that aims to co-produce knowledge with non-academic actors, e.g. marginalized groups, in order to develop research based on local concerns (Fraser et al. 2006). This is why I chose to include local small-scale farmers, fishermen, and pastoralists in the knowledge production in *Paper III*, since people with these livelihoods are directly affected by the socio-environmental changes in the region, yet excluded from the debates and decision-making about large-scale land acquisitions. I was interested to understand if, and how, people in the water-rich wetland areas of Kilombero Valley experience water-related challenges or conflicts (as suggested in *Paper II*), and if water really is the most

important challenge according to the participants. In this way, the research focus was not entirely pre-determined before going to the field, and knowledge could be co-produced with people in place. However, conflicting ideas and interests between local and non-local stakeholders make it difficult to navigate between the different actors in place, and it is therefore difficult to find the truth about what socio-environmental changes that are taking place. The confusion caused by conflicting ideas and interests was one of the reasons for developing *Paper IV*, partly in order to compare local perceptions with changes that can be observed in satellite images, but also to complement socio-environmental narratives from the ground with quantitative estimates of change, and maps of where the land cover changes occur. Important for this analysis was that land cover categories should be based on local categorizations of land cover classes, and bridge local concerns to a scientific understanding of change. Even though local people were not participating in the remote sensing analysis, the co-production of knowledge lies in that the analysis was developed from, and based on, local experiences and observations of change.

Figure 14. Example of a fully irrigated large-scale land acquisition. Images from Google Earth shows the previous land cover (desert) in 2007 to the left, and the current land use in the middle with wheat, alfalfa, potato irrigated with center pivot systems. Zooming out shows the digging of canals for irrigation purposes in the image to the right.

Conclusions

To sum up, I have investigated four key challenges that relate to contemporary trends in global land use, accounting for distal connections of land system change in the context of large-scale land acquisitions. Findings related to each challenge are summarised in the box below.

Challenge 1: Global shift in land ownership: what are the relationships between distant places?

Objective 1: *To map countries involved in the virtual trade of land through large-scale land acquisitions, and to describe their connectivity (global level).*

Findings: Land acquisitions are a telecoupled system where distal actors cause land system change elsewhere.

- 126 countries participate in the land trade network.
- The network is highly skewed, and a few countries dominate land trade. Main land 'importers' from the UK, USA, China, and land 'exporters' are Ethiopia, Madagascar, Philippines.
- The land acquisition network is prone to propagate crisis as changes in a few key countries can influence many other countries in the network.

Challenge 2: Risks of water conflict: how do land acquisitions affect blue and green water sources in Africa?

Objective 2: *To calculate water requirements of land acquisitions currently in production in Africa, and analyse how water demand has changed across a range of irrigation scenarios (continental level).*

Findings: Crops on acquired land require more water than traditional crops, and distant actors might contribute to water conflicts.

- Most crops grown on acquired land are not edible, but mainly for forestry and biofuel purposes.
- Water requirements primarily depend on crop type, but also on irrigation efficiency.
- 29-53 of 134 land deals are blue water hotspots, meaning that >50% water are from blue water sources, and are at high risk for water conflicts.

Challenge 3: Local perceptions of socio-environmental change: what socio-environmental changes and challenges do local farmers, fishermen, and pastoralists experience?

Objective 3: *To document perceptions of socio-environmental change, and to visualize the narratives as paintings (local level).*

Findings: Participants describe socio-environmental changes and challenges as complex interactions between cross-scale drivers, impacts, and feedbacks.

- Not only land acquisitions are causing socio-environmental change, but also population growth, and conservation areas contribute to increased pressures on land and water resources.
- Both case-study areas describe farmland explansion to the (protected) wetland area as a coupled effect of large-scale land acquisitions and population growth (more people on less land).

Challenge 4: Different ways of understanding socio-environmental change: How do local perceptions compare to quantifications of land cover change?

Objective 4: *To quantify land cover categories established in field with remote sensing, and compare with local perceptions of change (local level).*

Findings: The use of mixed methods point to aligning and diverging environmental changes.

- Farmland expansion to the wetland area can be identified (though with low accuracy) in the land cover classification, but the narratives of deforestation can not be strengthened by the remote sensing analysis.
- Mixing participatory methods and land cover classification points to aligning and diverging patterns of environmental change, which highlights the need for co-production of knowledge and use of mixed methods for future decision-making.

The *main empirical contributions* of this dissertation relate to the growing current competition for land and water resources, and how distal land connections cause socio-environmental impacts, and feedbacks elsewhere. They respond to key research gaps in land system science, which have been outlined by several authors in Seto and Reenberg (2014). *Firstly*, network analysis at the global scale made it possible to analyse land acquisitions as a telecoupled system, which is useful for identifying key players of the system, and how vulnerability and risk can spread between different countries. *Secondly*, hydrological modelling at the continental scale made it possible to obtain a refined understanding of hydrological change due to land acquisitions, a knowledge gap identified by numerous researchers who discuss large-scale land acquisitions as water grabs (Dell'Angelo et al. 2018; Dell'Angelo et al. 2017; Mehta et al. 2012; Woodhouse & Ganho 2011; Woodhouse 2012). My contribution consists in calculating and mapping blue and green water requirements of land acquisitions based on site-specific crops, climate, and irrigation alternatives (which improves previous estimates by Rulli et al. (2013)). These patterns can be used to identify areas that are likely to experience challenges and conflicts over water quantity due to high levels of blue water use. *Thirdly*, participatory research made it possible to understand local experiences of distal land connections, as well as future aspirations for change, which is crucial for developing pathways for a more sustainable future.

The *main methodological contributions* of this dissertation relate to developing participatory art as a way to co-produce knowledge, and thereby link local concerns to the scientific agenda, which is essential for facilitating sustainable development (Clark & Dickson 2003; Jerneck et al. 2011; Kates et al. 2001; Pohl et al. 2010; Verburg et al. 2013). The mixed-methods approach provided insights about knowledge production regarding socio-environmental change, in particular concerning complex feedbacks between farmland expansion, and the degradation of wetlands and forests. Aligning and diverging results from using bottom-up participatory approaches, and top-down land change detection methods, highlight the need to find contrasting and complementary ways to represent cross-scale feedbacks between changes related to population growth, conservation initiatives, and rapid land system changes in the context of large-scale land acquisitions.

A fisherman that I interviewed in Kilombero Valley told me *"I doubt that there will be any benefits in the future, regarding the current trends and how decisions are made."* This quote can be used to summarise my own conclusion and opinion about large-scale land acquisitions. With this dissertation, I add my voice to the growing body of scientific literature that highlights harmful socio-environmental effects of large-scale land acquisitions, including water stress and conflicts over water resources (Chiarelli et al. 2016; Franco et al. 2013), and complex feedbacks that accelerate land degradation, biodiversity loss, deforestation, and other land system changes (Bluwstein et al. 2018). Further research is needed to account for actual water changes caused by land acquisitions, and to better connect those hydrological changes to

demographic data and lived experiences. Possible refinements relate to water management on acquired land, and other site-specific parameters, e.g. what irrigation systems are used? How was the land used before being acquired? What are the local socio-hydrological changes? There is also a need to design sustainable solutions, based on local needs and aspirations. Such solutions should be developed in collaboration with affected communities, and could for example be based on scenario building.

Existing recommendations to stakeholders are often within the socio-economic realm; for example the Food and Agriculture Organization (FAO) recommends that "land contracts must be structured so as to maximise the investment's contribution to sustainable development" (Cotula 2009). Linking back to contemporary and future challenges of population growth, unequal distribution of consumption and production, and requirements to meet the Global Sustainable Development Goals, I see limited scope for land acquisitions to benefit all, facilitate sustainable development, or protect the environment. With the four papers of this thesis, I would therefore like to add a few socio-environmental recommendations for stakeholders.

Since there are no signs that the trend of global land acquisitions are abating, I suggest that crops grown on acquired land should be edible, and primarily produced to satisfy local or domestic food demands, in particular if land is acquired in countries with high food insecurity. I also suggest that crops planted should be suitable for that local climate, and low in water requirements in order to avoid conflicts over water quantity. If agribusinesses use irrigation, the irrigation systems should be of highest water use efficiency, like drip irrigation with pipelines as opposed to sprinkler irrigation. Consequently, if land acquisitions are to be considered as investments, they must be at the forefront of exploring more sustainable pathways of farming, by accounting for local needs, improving environmental conditions, and applying the latest scientific knowledge, no matter the economic cost. For example through implementing agro-ecological farming and organic agriculture that is low in imported synthetic input and contribute to restoring soils rather than degrading them (Liu et al. 2013b). From the socio-economic point of view, I suggest that local people should have the opportunity for education and long-term employment contracts at the farms, as opposed to temporary employment that seems to have little effect on bringing people out of poverty (Oya 2013). There is also scope for designing the investments differently. For example, farmers in Kilombero Valley suggest that they can do the farming, and that the agribusiness can provide storage for the harvest, packaging facilities, and connection to markets. This is similar to already existing outgrower schemes, which are often developed in parallel with the large-scale farms. These arrangements, however, seem to generate more benefits for already land-rich farmers rather than the land-poor (Herrmann 2017). A final reflection, in line with Liu et al. (2013b), is that no matter what arrangement, it is important to combine the strengths of the investor (capital and technology) with those of local farmers (labour, traditional know-how and knowledge of the local conditions).

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Architecture of the global land acquisition system: applying the tools of network science to identify key vulnerabilities

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Abstract
Global land acquisitions, often dubbed 'land grabbing' are increasingly becoming drivers of land change. We use the tools of network science to describe the connectivity of the global acquisition system. We find that 126 countries participate in this form of global land trade. Importers are concentrated in the Global North, the emerging economies of Asia, and the Middle East, while exporters are confined to the Global South and Eastern Europe. A small handful of countries account for the majority of land acquisitions (particularly China, the UK, and the US), the cumulative distribution of which is best described by a power law. We also find that countries with many land trading partners play a disproportionately central role in providing connectivity across the network with the shortest trading path between any two countries traversing either China, the US, or the UK over a third of the time. The land acquisition network is characterized by very few trading cliques and therefore characterized by a low degree of preferential trading or regionalization. We also show that countries with many export partners trade land with countries with few import partners, and vice versa, meaning that less developed countries have a large array of export partnerships with developed countries, but very few import partnerships (dissassortative relationship). Finally, we find that the structure of the network is potentially prone to propagating crises (e.g., if importing countries become dependent on crops exported from their land trading partners). This network analysis approach can be used to quantitatively analyze and understand telecoupled systems as well as to anticipate and diagnose the potential effects of telecoupling.

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Keywords: land grabbing, telecoupling, complex network, globalization, vulnerability, land systems science

1. Introduction

The issue of large-scale, trans-national land acquisitions (sometimes called 'land grabbing') has rocketed towards the top of the sustainability agenda in recent years. These deals involve public and private sector actors, including governments and agribusinesses, leasing or purchasing large tracts of land, mainly in developing countries in the Global South, for the production of goods of their choosing. Recent events that have triggered the rush for land include the rising cost of oil and the 2008 spike in food prices (Anseeuw *et al* 2012). These deals are controversial because they raise concerns

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about neo-colonialism, land tenure rights, and sustainable livelihoods for local communities in land-exporting countries (e.g., Anseeuw *et al* 2012). Meanwhile, others see such investments as opportunities for agricultural development and greater self-sufficiency in the Global South (Deininger *et al* 2011). Large-scale land acquisitions are rapidly evolving, and have the potential to quickly become a major driver of land change (Lazarus 2014). Indeed, there is mounting uneasiness that competition for food, energy and water, coupled with population increase, will result in a land 'bottleneck' (Lambin and Meyfroidt 2011).

Recent work has used analyses of international trade to allocate consumer responsibility for environmental impacts of goods produced internationally, including biodiversity loss (Lenzen *et al* 2012), CO_2 emissions (Davis and Caldeira 2010), and virtual water use (Hoekstra and Mekonnen 2012). This work focuses on how traded commodities, such as livestock, crops, and manufactured goods, result in global reallocation of the natural resources (e.g., land and water) used to produce them, often calling this 'virtual' trade to refer to the resources embedded in the production of the traded goods. Previous work has also analyzed the land embodied in goods produced for trade, finding for example that this 'land use displacement' where high-income countries acquire goods produced in low-income countries accounts for 6% of global land use (Weinzettel *et al* 2013). International trade of commodities (and of the land embedded in them) contribute to increasing environmental footprints associated with unsustainable production and consumption of goods globally (e.g., Hoekstra and Wiedmann 2014).

Global land acquisitions represent a new case within the domain of virtual land trade, where it is not only the yields or goods produced from land that is traded, but the ownership of the land itself. A recent analysis showed that substantial volumes of land have been traded through international land deals, totaling between 32.7 and 82.2 million hectares as of 2012. This corresponds to 0.75–1.75 of the Earth's agricultural land (Rulli *et al* 2013).

Land systems are increasingly globalized (Seto *et al* 2012, Yang *et al* 2013) and telecoupled, meaning human and natural systems are linked through socio-economic and environmental interactions over large distances (Liu *et al* 2013). Research priorities for telecoupled systems identified by Liu *et al* (2013) include adopting network approaches to analyze connections between multiple locations while increasing understanding of cross-system integration. Accomplishing this would help in generating new insights for evaluating changes in telecoupled systems. From this perspective, the global land acquisition system is inherently a telecoupled system that can be represented as a network, but it has yet to be studied as such (Liu *et al* 2013).

Recently, applying the tools of network science to large empirical datasets has enabled major strides in understanding in areas as diverse as brain function (Telesford *et al* 2011), international finance patterns (Vitali *et al* 2011), ecosystems (Proulx *et al* 2005), human migration (Davis *et al* 2013), and water trading (Konar *et al* 2011). *Topology* is a network science term that refers to the connectivity between nodes in a network (Heywood *et al* 2002), and in the context of this study describes how countries (nodes) are coupled to one another through land acquisitions (links). Note that topology refers to the patterns of connectivity only, and not the amount or use of land involved or the products derived from the land. The strength of this methodology lies in its ability to quickly analyze the relations between interacting components in a complex system in order to tease out structures that could yield insight into system functioning (e.g. Albert and Barabási 2002, Newman *et al* 2006).

In this article, we describe and analyze the structure of the global land acquisition system by representing it as network. Our first objective is to characterize the position of different countries in the topology of the land acquisition network in terms of: (a) the number of land trade partners associated with a country, and (b) the role that a country plays in connecting other countries to the network in a continuous chain, thereby contributing to global network integration. Our second objective is to identify the presence of land trading submarkets (relatively closed communities) embedded within the global land trade network. Our third objective is to discover whether countries tend to trade land with other countries with similar numbers of trading partners, or with dissimilar numbers of trading partners (which we term *trade orientation*). The latter would indicate an asymmetric trade system characterized by a small number of important global players that provide trade connections for a large number of peripheral countries. Finally, we briefly highlight the implications of our findings for vulnerabilities of the global land trade system in light of environmental or geopolitical stressors.

2. Data and methods

2.1. Land transactions data

In order to create the networks, we used two databases with collections of large-scale (>200 ha) land deals, retrieved October 2012: GRAIN (2012) and Land Matrix (Landportal.info 2012). At that time, the GRAIN database had 416 deals that were all trans-national, with a focus on food crops. The Land Matrix database contained 1006 deals, with a greater emphasis on flexible and fuel crops. Approximately 300 of these deals were internal, meaning that at least one of up to several investors were from the same country where the investment takes place.

To merge the GRAIN and Land Matrix deals into one database, we standardized country and crop labels following the FAO's country and crop naming conventions where available, including all trading partners in the case of deals with multiple importers. Duplicate deals between the two sources were identified by matching target country, investor country, number of hectares, crop(s) grown, and investor name, and the deal with more detailed information was retained while the other was deleted. Of the 1422 entries for

individual land deals, 48 were identified as duplicates and removed, leaving 1374 individual land trade deals, which were further aggregated according to import and export country (including all trading partners in the case of deals with multiple importers). These data were then analyzed using *Gephi* (Bastian *et al* 2009), an open-source software package for visualizing and analyzing large-scale networks, and UCINET, a software package for the analysis of social networks (Borgatti *et al* 2002).

2.2. Network approach

The land trading system can be depicted as a network where countries are linked by agreements that represent the transfer of land via purchase or lease. Using this approach, land traded between two countries defines a trade *link* that connects two countries (or *nodes*). Many countries trading land form a network of topological relations (or agreements) that can then be analyzed. For simplicity, we confine most of our more sophisticated analysis (objective 1b and objective 2) to examining the undirected land trade network. Specifying directionality to the links adds another level of complexity to the representation (country *A* leases or purchases land from country *B*, yielding an export of land from country *B* to country *A*) which we use for the analysis of objective 3. Note that in the land acquisition network, countries can both import (acquire) land from one country and/or export (sell) land to another country, which we call 'land trading.' As a matter of convenience, we use this terminology throughout the rest of the article in order to frame the analysis.

2.3. Objective 1—position of countries in the land trade network

2.3.1. Objective 1a: number of land trade partners. In order identify the key actors in the land trading system we ranked the countries according to their number of land trading partners (import partners, export partners, and their sum for total partners). Cumulative frequency distributions were also constructed in order to inspect the trade activity levels across the land trade network.

2.3.2. Objective 1b: role of country for providing network connectivity. To analyze the role a country plays for providing land trade network connectivity (thereby shaping cross-system behavior), we use the network analysis measure of normalized betweenness centrality and plot it against the number of trading partners for each country from objective 1a. Betweenness centrality for a country counts the effective number of times that country lies on the shortest path (minimum number of trade links) 'between' all other country pairs in the network (e.g. Freeman 1977, Newman 2010). Betweenness centrality goes beyond using the information on a country's local trading activity from its number of land trade partners. Rather, it is a measure that gives information about the load that a country bears for ensuring that countries are sequentially connected across the network in an unbroken chain. It is computed by counting the number of times a country of interest intercepts the shortest pathway between all other country pairs in the network, divided by the number of shortest paths between all country pairs, before finally summing across all of these proportions for every country in the network. Therefore, if a country of interest does not possess the only shortest pathway between two other countries, its influence is reduced in the computation by increasing the denominator. Note that the word *chain* here implies that the one trade link connecting a pair of countries can join up with another trade link connecting another country pair where one of the countries in these two pairs is a member of both pairs. In this way, a gap-free chain of agreements is built up across the network. We therefore underscore that the word *chain* does not refer to the production *chains* commonly analyzed in multi-regional input–output analysis from economics (e.g., Moran *et al* 2013), or the material and energy flow analysis common in industrial ecology (e.g., Suh 2005), where raw materials exported by country *A* are processed by country *B* and the product is exported further to country *C*.

Here we report normalized betweenness centrality by dividing the betweenness centrality of a country by the total number of country pairs in the network (excluding the country for which betweenness centrality is calculated) (e.g. Newman 2003). This produces a value between 0 and 1 (and often expressed as a percentage), where a value near 1 (100%) indicates a central player ensuring that countries are connected in an unbroken sequence across the network, and a value near 0 indicating a more peripheral country that is relatively uninfluential in the broader network. For further information on calculations for network metrics, see supplementary material A, available at stacks.iop.org/ERL/9/114006/mmedia.

2.4. Objective 2—land trade submarkets

To identify the existence of land trading submarkets, we used the local clustering coefficient (e.g., Watts and Strogatz 1998, Borgatti *et al* 2002) which quantifies the extent to which subsets of countries form dense land trading relations among themselves, and sparse trading relations with other countries (e.g., Piccardi and Tajoli 2012). The local clustering coefficient is computed as the ratio between the number of land trades that occur between the direct trading partners of a country of interest and the theoretical maximum number of land trades that could potentially occur between those same partners. The local clustering coefficient can take any value between 0 and 1, with 0 indicating that none of the trading partners of a country of interest trade land with one another, and 1 indicating that every trading partner for a given country of interest has direct trade ties with one another. For further information, see supplementary material A.

2.5. Objective 3—land trade orientation

Finally, we examined whether countries tend to trade land with other countries with similar numbers of trading partners

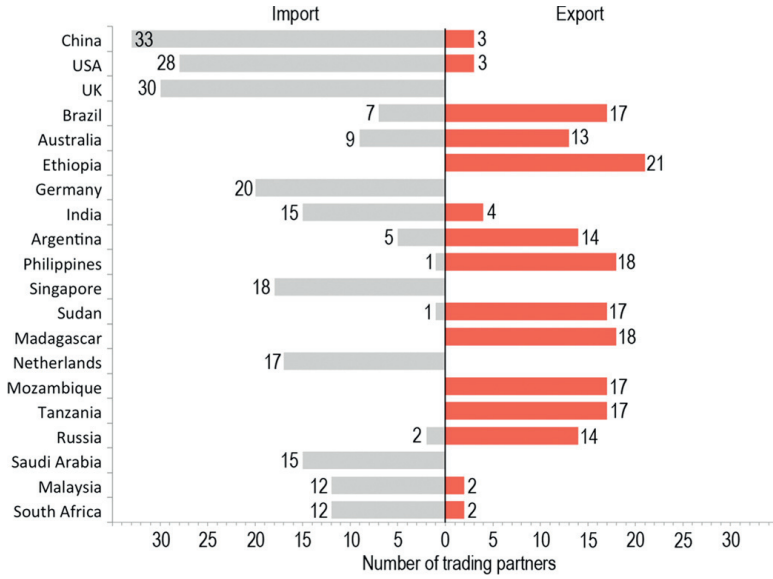

Figure 1. The top 20 countries in the global land trade network, ordered by the largest number of trading partners. The list is also partitioned by number of import partners (gray bars) and number of export partners (red bars).

(which we term *assortative trade orientation*), or whether countries tend to trade with other countries with dissimilar numbers of trading partners (which we term *disassortative trade orientation*). Assortative trade orientation would occur if a country with many trading partners traded with other countries with many partners themselves (or if countries with few trading partners traded with each other). Disassortative trade orientation would occur if countries with many (few) trading partners trade land with other countries with few (many) trading partners. We examined land trade orientation using the metric of average nearest neighbor degree, and plotted this metric against the number of trading partners. Here, neighbor is not used in a geographic sense, but rather refers to countries that share a direct trading relationship. For example, though Sweden and Tanzania are not geographical neighbors, they are trading neighbors. For a country of interest, the average nearest neighbor degree is computed by first counting its number of trading partners. Thereafter, a tally is made of the total number of trading partners that, in turn, each of the trading partners of the country of interest has. Finally, this latter value is divided by the former value to obtain average nearest neighbor degree (e.g. Pastor-Satorras *et al* 2001, Newman 2003, Konar *et al* 2011). For the analysis of land trade orientation, we considered direction of trade (import or export) in order yield general insights regarding the country-level factors that may lie behind any observed trade asymmetries. More details can be found in supplementary material A.

3. Results and discussion

3.1. Objective 1—position of countries in the land trade network

3.1.1. Objective 1a: number of land trade partners. Out of the 195 countries recognized by the UN as of 2013, 126 (or 65%) participate in land trading. We found a total of 471 land trade relationships between these countries, which included 40 countries with one local import partner in addition to international partners. We removed these reflexive links from our analysis, thereby reducing the number of links from 471 to 431.

We found that the land trade network is dominated by a small number of countries that trade land with a large number of partners, with many additional countries playing minor roles by only trading with one or a few partners. Considering all trades without reference to the trading role played (land importer or exporter), China tops the list for total number of trading partners (36), followed by the US (31), UK (30), Brazil (24) and Australia (22) (figure 1).

There are 70 countries importing land, which represents 55% of all countries in the network, but most of these also engage in exporting land (figure 2); relatively few countries (24 in total or 19%) act purely as land importers. For all importing countries, China again dominates, importing land from 33 countries, with the UK (30), US (28), Germany (20), and Singapore (18) rounding off the top five (figure 1). The importing countries are geographically clustered in North America, the Middle East,

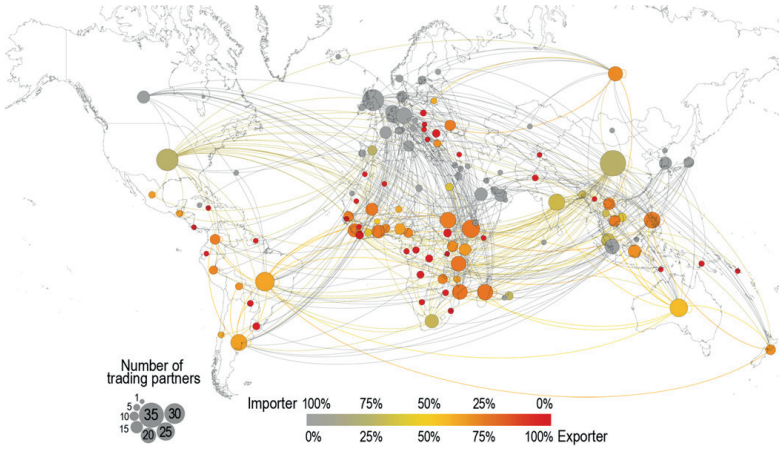

Figure 2. Map of the land trading network. The color of the node shows to what extent a country is an importer (gray) or an exporter of land (red), and the size of the node represents the number of trading partners. The links represent the flow of land acquired by an importer from an exporter. Link colors are that of the importing node. Number of countries (nodes) = 126, while number of land trade relationships (links) = 471 (reflexive links shown, e.g., loop for China having a national partner involved in land trade along with international partners).

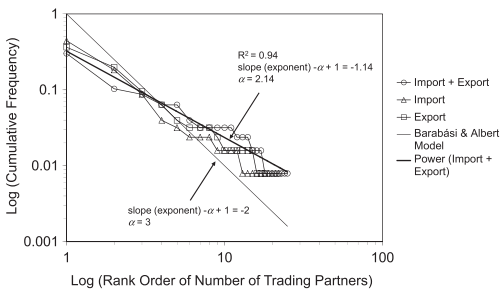

Figure 3. Cumulative frequency distributions (rank/frequency plot) of number of trading partners per country for the 126 countries participating in international land trades for both land imports and exports (circles), imports only (triangles), and exports only (squares). The thick curve is a power law fitted to imports and exports with slope (exponent) $-\alpha+1$, with $\alpha=2.14$ and $R^2=0.94$. The thin curve represents a power law with slope $-\alpha+1$, with $\alpha=3$, conforming to the preferential attachment model of Barabási and Albert (1999). Construction of the cumulative frequency distributions follow the method given in appendix A of Newman (2005).

Western Europe, and Asia (figure 2). The number of exporting countries total 80, which represents 63% of all countries in the network, with most of these (56 countries, or 44%) acting purely as land exporters. The exporting country with the most trading partners is Ethiopia, which exports land to 21 countries, followed by Madagascar (18), Philippines (18), Brazil (17), and Mozambique (17). Exporting countries generally consist of less developed countries and are concentrated in Africa, South America, Southeast Asia, and Eastern Europe (figure 2). This highlights the fact that the division between land importing and exporting nations is an economic one, where land resources are being transferred from the Global South to the Global North.

A total of 46 nations in the network (37%) are both importers and exporters of land (particularly those located in Asia and Eastern Europe), including two of the top five in terms of total trading partners (Australia and Brazil). For example, of Australia's total of 22 trading partners, it exports land to 13 partners and imports land from nine others. Despite this, most countries (63%) play only one role (importer or exporter) in the land trade system.

Most countries participating in global land trade, either as importers or exporters, are involved with only one or very few partners, underscoring the dominance of a very small number of countries in the land trade system (see figure 3, which contains cumulative frequency distributions showing the fraction of countries with number of trading partners greater than or equal to a certain size). A majority of exporting countries (70%) export land to six or fewer countries, with only 24 countries exporting land to seven or more partners. Trading is even more concentrated in importing countries, where 33% import from only one partner, and only 21 countries import land from seven or more partners.

Note that figure 3 shows that the cumulative frequency distribution of land trading partners (imports + exports) also conforms to a power law with exponent (slope in figure 3) equal to $-\alpha+1$, where in this case $\alpha=2.14$ and $R^2=0.94$ (thick curve—see Newman (2005), for further details on power laws). The power law relationship implies that the network is *scale-free*, meaning that a typical number of trading partners for a country cannot be defined, and that the shape of the distribution remains unchanged across all domains of the distribution.

Though α is within the range of values typical for a great number of natural and some social systems, $\alpha=3$ would be expected for a network characterized by a pure *preferential attachment* process described by the Barabási and Albert

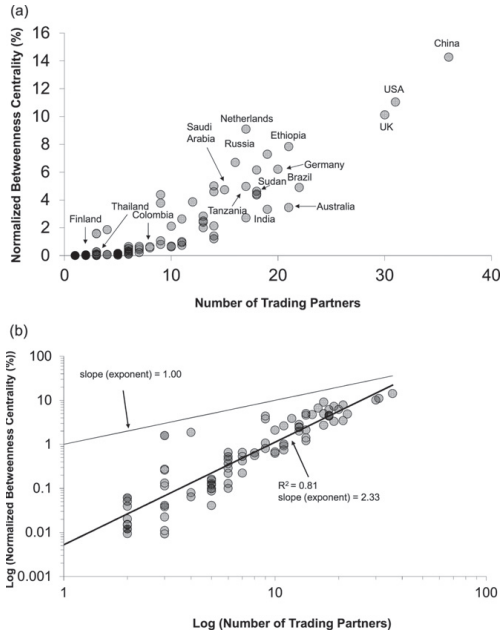

Figure 4. (a) Normalized betweenness centrality versus number of land trading partners (imports + exports) for 126 countries in the land trade network (circles). Circle shade intensity indicates degree of overlap between data points (the more circles that overlap, the darker the shade). A high normalized betweenness centrality indicates a globally influential country that is responsible for connecting many other countries in an unbroken sequence across the network, and a value near 0 indicates a more peripheral country that is relatively uninfluential in the broader network. (b) Same as (a) but on log–log scale, showing that the relationship between normalized betweenness centrality and number of land trading partners (imports + exports) follows a power law with slope (exponent) of 2.33 and $R^2 = 0.81$. A power law with slope (exponent) 1 is shown for comparison.

(1999) model (thin curve in figure 3). Since $\alpha < 3$, we hypothesize that this mechanism is constrained by geography, political relations, legal frameworks and colonial ties. For example, it might be easier for countries to forge land deals with partners that are geographical neighbors, or with partners that share common history or language. One potential implication of the preferential attachment process is that those countries with many trading partners will tend to accumulate even more trading partners over time, making them increasingly dominant players in the global land trade system. This tendency is a feature of a great number of natural and some social systems (Barabási and Albert 1999). The economic opportunity and/or need amongst some of the land-rich countries across the Global South, coupled with the demand and financial means amongst some of the more land-impoverished countries of the Global North would mean that these two groups would have greater visibility in the land acquisition markets through promoting themselves. This would conceivably lead to a positive feedback in the number of trading partners they accumulate over time.

3.1.2. Objective 1b: role of country for providing network connectivity. In general, we find that countries with many trading partners also play a more important role in providing network integrity as shown by their high normalized betweenness centrality scores, while those with few trading partners have low normalized betweenness centrality scores (figure 4(a)). The association is weakly nonlinear, indicating that as the number of trading partners increases, a country has proportionally greater influence in contributing to trade connectivity of the network. The average normalized betweenness centrality score for the entire land trading network is 1.4%, meaning that on average, any given country in the network lies on the shortest path between any two other countries only 1.4% of the time. Three countries (China, the US, and the UK) have normalized betweenness centrality scores over 10%, meaning that individually, these countries are found along the shortest trading paths between more than 10% of all other country pairs in the network. A total of 41 countries (33% of those in the network) with normalized betweenness centrality scores of 0 represent the outer periphery of the network and possess only one direct trading partner. Note that figure 4(b) shows that the relationship between number of trading partners and normalized betweenness centrality is best fit by a power law with slope (exponent) = 2.33, accompanied by a $R^2 = 0.81$ (thick curve). The thin curve shows a model with slope (exponent) = 1.0 for comparison. That this relationship also follows a power law is to be expected given its correlation with number of trading partners (the distribution of which is also best fit by a power law), while the slope (exponent) near 2 indicates that the land acquisition network has a well-developed branching structure (e.g., Barthélemy 2004).

The Netherlands is an anomaly because it has a normalized betweenness centrality score almost as large as the UK (figure 4(a)) despite having half as many trading partners, meaning its relatively few trading partners are strategically important for providing network connectivity. The Netherlands has for many centuries functioned as a transportation hub due to its strategic maritime position, coordinating the traffic of goods and services between Europe and the rest of the world. Previous studies concerning the global trade network of agriculture and finance show that the Netherlands has played a disproportionately large role for coordinating global trade, as indicated by high betweenness centrality scores computed for finance (De Benedictis and Tajoli 2011, Ercsey-Ravasz *et al* 2012) and water (Konar *et al* 2011) networks. As the land trade network is a subset of the larger global trade network, it is reasonable to assume that it would inherit some of the larger network's features (see section 3.4).

3.2. Objective 2—land trade submarkets

Overall, the land trade network displays a low incidence of clustering and therefore a high degree of global homogeneity

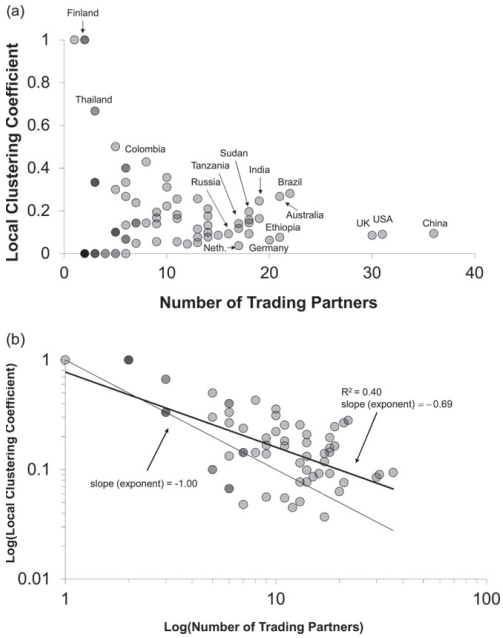

Figure 5. (a) Local clustering coefficient versus number of trading partners (imports + exports) for 126 countries in the global land trade network (circles). Circle shade intensity indicates degree of overlap between data points (the more circles that overlap, the darker the shade). The local clustering coefficient identifies the existence of trading submarkets in the network, where countries with values near 1 indicate that their trading partners form dense land trade connections with one another (trading submarket) while values near 0 indicate sparse trading links between its trading partners. (b) Same as (a) but on log–log scale, showing that the relationship between normalized betweenness centrality and number of land trading partners (imports + exports) is best fit by a power law with slope (exponent) of −0.69 and $R^2 = 0.40$. A power law with slope (exponent) of −1 is shown for comparison.The power law combined with the weak correlation coefficient suggests that the organization of submarkets is weakly hierarchical.

and integration. This is shown by the fact that most countries in the land trade network have a small local clustering coefficient, with a mean for the entire network of 0.17. This implies that only 17% of all potential trading ties are established between the trading partners of a country, on average. Figure 5(a) shows that although the relationships between local clustering coefficient and number of trading partners exhibit considerable scatter, the local clustering coefficient decreases as the number of trading partners increase. But we also note that many countries with few trading partners also have low local clustering coefficients.

Despite the overall low level of clustering, a few distinct submarkets exist in the global land trade network, where trading partners are well-connected both directly to each other, and indirectly through one intermediary country with whom they both trade. For example, Finland has a local clustering coefficient of 1.0 (figure 5(a)), meaning that Finland's trading partners (Sudan and China) also trade land with each other. Note, however, that this does not imply that Sudan and China are trading land exclusively with each other and with Finland, as Sudan and China also have many other trading partners and themselves possess low local clustering coefficients (0.20 and 0.09 respectively). Countries with low numbers of trading partners, therefore, can form trading cliques where the trading partners of these countries also trade land with one another.

Most countries, in particular those with many trading partners, have low local clustering coefficients around 0.1, including the UK, the US, and China. This means that only 10% of the potential trading links between China's trading partners are realized. Therefore those countries with many trading partners function to bring those countries with a low number of trading partners into the land trading network.

We hypothesize that land trade relations for countries with moderate or high local clustering coefficients could be shaped by pre-established historical, geographical, political, and colonial ties. An example from our study would the land trading ties that bind Swaziland (local clustering coefficient of 1), the UK, and South Africa; further investigating this hypothesis across the land trade network would require detailed case studies.

We also hypothesize that the land trade network is weakly hierarchical, where trading between small trading submarkets undergirds the less vigorous trading between larger, more weakly connected submarkets and so on. This is because there exists a moderately weak power law relationship between the clustering coefficient and number of trading partners with slope (exponent) = −0.69 and $R^2 = 0.40$ (thick curve) (figure 5(b)). Networks that are strongly hierarchical yield slopes (exponents) very close to −1 (see the thin curve in figure 5(b) for comparison) (e.g., Ravasz and Barabási 2003). We propose that geography imposes an organizational structure onto the land trade network that acts to pull the slope (exponent) of the relationship closer to 0. Such an effect (though more extreme) has been demonstrated in networks more purely organized by geographical location such as the power grid and internet routers (Ravasz and Barabási 2003).

3.3. Objective 3—land trade orientation

In comparing the trading activity level of countries with their import and export partners (land trade orientation using nearest neighbor degree), we found no clear relationship between number of import (figure 6(a)) or export (figure 6(c)) partners for countries of interest (located on the x-axis) and their trading partners (in both cases, slope is near 0 with an $R^2 < 0.01$). There was a slight tendency towards disassortativity for countries with many import partners to trade with countries with many export relationships (figure 6(b) has a negative slope, $R^2 = 0.16$). For example, Kenya imports land from two countries (Sudan and Tanzania) that in turn export land to 17 other countries on average. There was a moderately

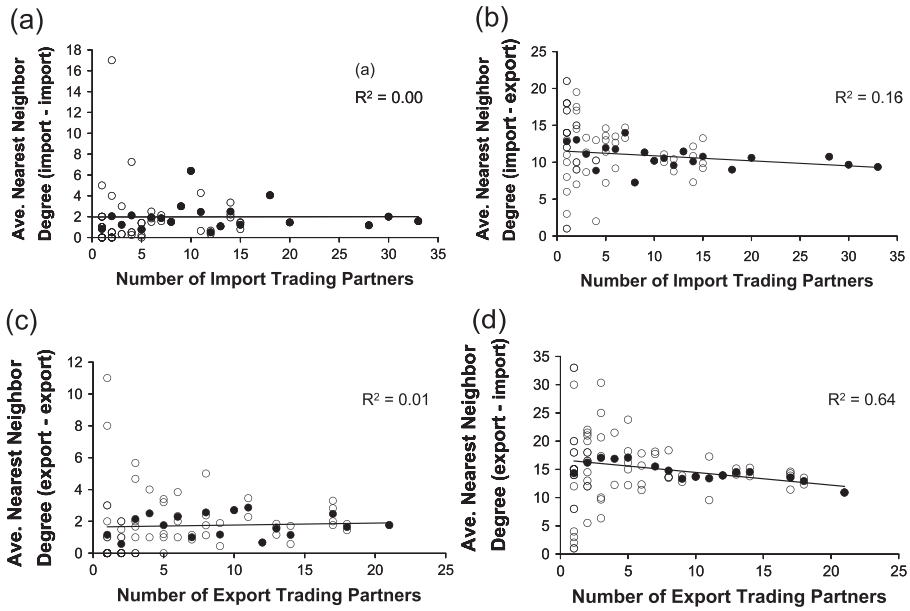

Figure 6. Average nearest neighbor degree versus number of trading partners four land trade orientations: (a) number of import partners versus average number of import partners of nearest neighbors. (b) Number of import partners versus average number of export partners of nearest neighbors. (c) Number of export partners versus average number of export partners of nearest neighbors. (d) Number of export partners versus average number of import partners of nearest neighbors. Open circles are average nearest neighbor degree per country, while the solid circles are means per 'number of trading partner' class. The solid line is a least squares regression through the means (solid circles) with an associated coefficient of determination (R^2). Negative slopes indicate disassortative land trade orientation where countries with many (few) trading partners trade land with other countries with few (many) trading partners.

strong disassortative relationship where countries with a low (high) number of export partners show a strong preference for trading land with countries having a high (low) number of import partners (figure 6(d) has a steeper negative slope, with $R^2 = 0.64$). Examples include Cameroon, which exports land to six countries that in turn import land from 17.8 countries on average.

For figures 6(a)–(d), note the steep decrease in the range of average nearest neighbor values (open circles) with increasing trade activity for all instances, meaning that the pool of countries with high trade activity decreases considerably, thereby severely limiting the number of average nearest neighbor degree observations for a given country with vigorous trade activity. This is to be expected, as we have shown that very few countries are highly active land traders (section 3.1).

The slight to moderate disassortativity shown in figures 6(b) and (d) implies that less developed countries tend to have a large array of export partnerships with wealthy countries, but import little land themselves. For example, Ethiopia exports land to 21 countries located in the Global North and to the more developed parts of Asia and the Middle East, but does not import any land at all. It is also evident that some more developed countries cast a diverse net and import land from many other countries, thus plugging them into the global land trade network, but do not export much land. An example is China, importing land from 33 countries but exporting land to only three. However, those countries that simultaneously have larger numbers of both import and export partners provide exceptions to these generalizations and act to weaken the relationships in figure 6. Examples include Australia and Brazil, who export to 13 and 17 partners respectively, while importing from nine and seven partners.

We hypothesize that vigorous importers of land trading land with one another would not yield financial benefits because land resources are either expensive or scarce in these countries, which is why they seek to import land from the exporting countries where it is more cheap and plentiful. As an example, Saudi Arabia has 15 exporting partners, most of which are located in Africa. Additionally, exporting countries trading land with one another would not yield benefits as these countries would already have adequate land resources and would therefore seek to export their land to those countries that desire land for various reasons. An example would be Ethiopia, which exports land to 17 other countries mostly located in the Global North and the richer parts of the Middle East. These types of relations likely underlie the weaker relationships evident in figures 6(a) and (c).

A multitude of other factors could also contribute to the reduction in disassortativity and large scatter in average

nearest neighbor degree, particularly for low levels of trade (open circles) in figure 6. For example, while countries tend to form trading partnerships with other countries that already have high trade activity, certain types of land trade partnerships may be forged due to the existence of geographical, historical, colonial, legal and linguistic ties. A similar interpretation is provided by Davis *et al* (2013) in order to account for similarly weak patterns in their study of global human migration.

3.4. Comparison with the global agricultural trade network

Recent work has used network analysis to characterize trade in agricultural products, particularly by focusing on the virtual water embedded in some internationally traded crops and food products (Konar *et al* 2011, Suweis *et al* 2011, Dalin *et al* 2012). These analyses include a much larger fraction of global agricultural production (e.g., 60% of global calorie consumption in Dalin *et al* (2012)) than the land trade network analyzed here, although our analysis also includes deals producing flexible or fuel crops as well as food. Thus, we will briefly compare some of the broad similarities and differences between these previous analyses of larger networks of global food production, and our analysis focusing on production of crops for a variety of purposes on internationally acquired land.

Firstly, it is apparent that countries located in the Global South are completely absent from the top traders in these larger networks (e.g., Konar *et al* 2011) presumably because they are restricted to subsistence trade flows. The prominence, therefore, of a great many of countries located in the Global South in the land acquisition system represents a novel development in global trade systems.

Topologically, the land acquisition network is much smaller in terms of mean number of trade links per country, as well as total number of trade links, by factors of about seven and ten respectively, compared to the larger trade networks (e.g. Konar *et al* 2011, Suweis *et al* 2011, Dalin *et al* 2012). The larger networks are also characterized by the dominance of a small number of countries but their cumulative frequency distributions of trading partners are best fit by exponential models, unlike the power law we found for land acquisitions (e.g., Konar *et al* 2011, Dalin *et al* 2012). Furthermore a greater degree of regionalization in these larger networks is apparent as can be seen from a much higher degree of local clustering. Like the land acquisition network, a strong dependence of betweenness centrality on number of trading partners is also observed in the larger networks (Konar *et al* 2011, Suweis *et al* 2011)

We speculate that these structural differences are due to the fact that the global agricultural trade network represents a more mature configuration where the growth of the network has slowed considerably and changes in network size are restricted to the addition and removal of trade links between already participating countries rather than the addition of new participant countries. Additionally, economically powerful countries that have long been at the core of the global agricultural network may no longer be forging new trade relations as quickly and are giving way to the emergence of a new set of second tier, but still influential actors (e.g., De Benedictis and Tajoli 2011). All of these factors would contribute to the reduction of a well-developed 'core–periphery' pattern still found in the land trade network. That the cumulative frequency distribution of trading partners for the large agricultural trade network is best fit by an exponential model rather than a power law also suggests a significant deviation from the preferential attachment process described by the Barabási and Albert (1999) model (see section 3.1) and lends some support to these arguments.

3.5. Vulnerabilities arising from land trade telecoupling

From a risk perspective, environmental or geopolitical stressors affecting a country that is tightly woven into the land trade network could efficiently transfer such a crisis to many other countries. For example, Ethiopia is a land export hub, selling or leasing land to 21 countries in the network (figure 1). Ethiopia also has a relatively high normalized betweenness centrality (7.8%), meaning that it plays a prominent role in indirectly connecting many other countries through land trading. Should any country become dependent on Ethiopia for future food imports (e.g., Saudi Arabia), a famine in Ethiopia could lead to price hikes in dependent countries. Such a price ripple could spread across many other countries indirectly through the importing country.

We note that many areas of land export are concentrated in regions with moderate to high yield gaps such as sub-Saharan Africa and Eastern Europe (Mueller *et al* 2012); such areas have the potential to increase yields through increased technology and management from foreign partners, but also to transfer risk throughout the network under stress. These countries would also be internally vulnerable to the vagaries of the global markets because investors on the ground (e.g. government or corporate importers of land) could suddenly pull out, therefore saddling the exporting country with various problems.

We have also shown that countries that have a large number of export partners tend to trade land with countries that have a low number of import partners (disassortative relationship in figure 6(d)), implying that such a stressor could simultaneously reach a diverse array of import countries in the network. In line with this, there is evidence that the structure of the land trading network is fragile. Simulation experiments by Newman (2002) show that networks that are either disassortative or randomly arranged (neither assortative nor disassortative) are more unstable, and thus more vulnerable to disintegration, compared to networks that show assortative properties. Topologically, this would entail a major decline in a node's number of links or the deletion of a node. In terms of the land trade network, this would be equivalent to a decline or disappearance of a country from the land trade network due to a decrease or elimination trade relations from changes in natural resource availability or economic status.

We speculate that countries belonging to land trade submarkets may be buffered against geopolitical and

environmental disturbance (caused by or causing changes in natural resource availability) because of decreased dependence on global land trade. Local clustering has been shown to lead to robust function in biological networks (Kashtan and Alon 2005). But the rare occurrence of submarkets in the land trade system (indicated by a low average clustering coefficient, 0.17) is suggestive of a highly integrated globalized system that would be more prone to the efficient spread of a crisis.

The emerging paradigms of teleconnections and telecouplings in the land and sustainability sciences (Seto *et al* 2012, Liu *et al* 2013, Yang *et al* 2013) recognize that the planet is shrinking due to the interconnectivities associated with global trade. While there may be a large geographical separation between trading nations, the relational distances can be small by virtue of these trade connections. Recent work has underscored the vulnerability of geographically distant places and people to environmental stressors (Adger *et al* 2008), which can undermine institutional structures that aim to protect human rights and ecosystem services (Sikor *et al* 2013). On an interconnected planet, such crises can spread well beyond their places of origin while simultaneously interacting and synchronizing with events elsewhere (Biggs *et al* 2011). In this paper, we point to an explicit framework for tracing such perturbations through the land trading system.

Other analytical frameworks such as multi-regional input–output analysis from economics (e.g., Moran *et al* 2013) and material and energy flow analysis common in industrial ecology (e.g., Suh 2005) also use network representations. To the best of our understanding, these approaches are designed to be used with data on flows energy, resources, or money across a chain of inputs and outputs in well-defined systems. Conceivably, these methods could be applied successfully to the land acquisition system, but a larger number of assumptions and a different kind of data would be required to implement them. This combined with a lack of appropriate and reliable data about land acquisitions motivates our application of a more inductive, data-mining framework (that of complex networks) that facilitates a general and fundamental understanding of system structure and function.

We recognize several possible limitations of this study that would benefit from further analysis. One limitation in our study entails our choice of country as the unit of analysis. Though most global-level studies associated with trade apply similar, or even coarser levels of aggregation (e.g., FAO regions), this level of aggregation obscures the role that corporations and financial markets play in shaping land acquisitions. These entities may not be wholly acting in the interests of the country, though they may be subjected to some form of regulation. Another uncertainty entails the reliability of the land transaction data itself, at the sub-country level. Though we merged two databases in order to establish a more complete pool of data with which to work, the data reporting is often incomplete and inaccurate, partly due to the lack of standardization in reporting, and partly due to poor transparency by those engaged in land trades (e.g., Edelman 2013, Oya 2013, Pearce 2013). The data are also subject to change as new information comes to light. For example, new countries not previously represented in our database may enter the land trade network, or new agreements may be established between countries already engaged in the land trade network that did not previously trade land with each other.

Nevertheless, in spite of frequent changes to these databases, we expect that our data (aggregated to the country level) would be insensitive to errors in over- or under-reporting of specific deals already established between actors (governments, private firms) within two specific countries already participating in land trading. This is because it is sufficient to have one deal established between actors in two countries in order to define a link at the country-level. A greater number of deals established at a sub-country level would not produce a greater number of trade links at the country level. Finally, it remains to be seen whether the overall properties of the land trading system (characterized by strong hierarchical ordering in land trade connections and betweenness centrality, low level of local clustering, and weak to moderate disassortativity) will remain consistent over the long-term as various countries may shift their relative positions within the network over time, and as new countries enter into land trading.

4. Conclusions

To the best of our knowledge, we have provided the first exploratory, top-down analysis of the topology of the land trading system using a complex networks approach. We have shown that trade activity conforms to a well-developed hierarchy, with a small number of countries showing high trading activity for both import and export of land. Importing nations are concentrated in the Global North, the emerging economies of Asia, and the Middle East, while exporting nations are generally concentrated in the Global South and Eastern Europe where yield gaps are highest, as well as areas with mixed yield performance including South America and Southeast Asia. We have also shown that the land trade network is highly integrated and globalized, with a small number of countries responsible for connecting the system. This result is further underscored by the overall weak level of preferential or regional land trading signified by the small number of land trade submarkets. Finally, we have shown that the land trading system is weakly disassortative. Many of our results underscore the potential fragility of the network.

We have also contributed to advancing research in telecoupling by applying the tools of network science for describing the architecture and cross-scale integration of the global land trade system. Such a global analytical framework is useful for generating insights about how changes in the global land trade system over time could influence its functioning (as we have demonstrated). Insights of this kind could be applied to other global systems such as migration of people and species, and transfers of physical, financial, and knowledge resources to better understand and manage an increasingly globalized world.

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Paper II

Green and blue water demand from large-scale land acquisitions in Africa

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In the last decade, more than 22 million ha of land have been contracted to large-scale land acquisitions in Africa, leading to increased pressures, competition, and conflicts over freshwater resources. Currently, 3% of contracted land is in production, for which we model site-specific water demands to indicate where freshwater appropriation might pose high socioenvironmental challenges. We use the dynamic global vegetation model Lund–Potsdam–Jena managed Land to simulate green (precipitation stored in soils and consumed by plants through evapotranspiration) and blue (extracted from rivers, lakes, aquifers, and dams) water demand and crop yields for seven irrigation scenarios, and compare these data with two baseline scenarios of staple crops representing previous water demand. We find that most land acquisitions are planted with crops that demand large volumes of water (>9,000 $m^3 \cdot ha^{-1}$) like sugarcane, jatropha, and eucalyptus, and that staple crops have lower water requirements (<7,000 $m^3 \cdot ha^{-1}$). Blue water demand varies with irrigation system, crop choice, and climate. Even if the most efficient irrigation systems were implemented, 18% of the land acquisitions, totaling 91,000 ha, would still require more than 50% of water from blue water sources. These hotspots indicate areas at risk for transgressing regional constraints for freshwater use as a result of overconsumption of blue water, where socioenvironmental systems might face increased conflicts and tensions over water resources.

land grabbing | water scarcity | LPJmL | water footprints | irrigation

Increased Competition Over Freshwater Resources

Freshwater is becoming increasingly scarce in many regions of the world, a result of both unsustainable land management and changes in rainfall patterns as a consequence of global and regional climate change (1). Moreover, the demand for water is increasing because of population growth, higher food demand, and changing dietary preferences, as well as increased industrialization and urbanization. Water, food, and energy are closely linked, and fundamental for human well-being, poverty alleviation, and sustainable development (2). As demand for water, food, and energy increases, there is an increased competition for water resources between agriculture, livestock, fisheries, forestry, energy, and other sectors, with unpredictable impacts for livelihoods and the environment.

Globally, agriculture is the most water-consuming sector, responsible for 70% of global freshwater withdrawals and more than 90% of consumptive water use (3). Agriculture's freshwater use is causing severe environmental degradation in many parts of the world (4). This in turn affects local ecosystems and people, especially in countries where the population directly depends on the surrounding environment for their livelihoods. For example, Lake Chad has shrunk by 95% since 1963 as a result of large-scale irrigation projects in Chad, Nigeria, Niger, and Cameroon together with climatic changes (4). This is just one example of how large-scale irrigation has contributed to local water scarcity, and in turn harmed societies and ecosystems.

Large-scale conversion of land to agriculture to provide food, fiber, and energy needs to balance trade-offs between agricultural production, and other societal and ecosystem needs (5). It is important to weigh the benefits of increasing yields through irrigation with the consequences those water extractions might have on local and regional scales. The cumulative effect of local land-use changes also have regional to global consequences, to the degree that regional boundaries of freshwater use are transgressed, thereby increasing the risk for abrupt and irreversible environmental change (6), potentially creating new challenges for food, fiber, and energy supplies.

Green and Blue Water in Agricultural Production

Water embedded in agricultural production can be divided into site-specific precipitation stored in soils and consumed by plants through evapotranspiration (green) and surface and ground water in aquifers, rivers, lakes, and dams that can be extracted from renewable and nonrenewable sources for irrigation (blue) (7). Blue water is sometimes diverted from nonlocal sources to enable agricultural production (8). The volume of blue water required by agricultural systems differs, depending on crops planted, agricultural management, and water lost through evaporation from the water source to the field. The green and blue water concept can help estimate site-specific water demand of agriculture, and refine our understanding of human impacts on freshwater resources. Distinguishing between blue and green water indicates the volume of freshwater needed to meet human demands in addition to what is available through precipitation. These blue water extractions in turn might pose increased competition or conflicts between other water-using sectors.

Significance

Freshwater appropriation can have vast impacts, depending on management and scale of water use. Since 2000, foreign investors have contracted an area the size of the United Kingdom in Africa, leading to increased pressure on water resources. Here we couple site-specific water demand for the crops planted there to the efficiency of different irrigation systems, while relating these estimates to local water availability. This approach enables us to identify "hotspot" areas of freshwater use where crops demand more water from irrigation than can be supplied by soil moisture, where the potential water demands from large-scale land acquisitions pose a risk for increased competition over water resources. Of these land acquisitions, 18% would be hotspots even with the most efficient irrigation system implemented.

Author contributions: E.L.J., J.W.S., and K.A.N. designed research; E.L.J. performed research; E.L.J. and M.F. contributed analytic tools; E.L.J. and M.F. analyzed data; M.F. parameterized and modeled crops and performed water requirement simulations with LPJmL; and E.L.J. wrote the paper, with contributions of M.F., J.W.S., and K.A.N.

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SUSTAINABILITY SCIENCE

Large-Scale Land Acquisitions and Freshwater Appropriation

Large-scale land acquisitions are areas larger than 200 ha contracted for commercial agriculture, for the purpose of timber extraction, carbon trading, food, feed, and renewable energy production (9). In 2014 the land-monitoring initiative Land Matrix had registered about 47 million ha of land contracted globally since 2000 under such large-scale land acquisitions. All deals in the database have at least one transnational investor from the public or private sector (including individuals, companies, investment funds, and state agencies), and may also include one or more domestic investors. These investors are currently key players in the modernization of African agriculture, and imply a conversion from smallholder production or community use to a commercial use of land and water (10).

The reasons for the rush for land are many, but were partly triggered by the food and energy crisis of 2007–2008 (11). Globalization, market liberalization, and commodification of land and natural resources in combination with the support of international donors have facilitated the implementation of these land contracts (11). Governments in the targeted countries may see foreign investments in land as an opportunity for agricultural modernization (10), as investors often motivate and legitimize their business proposals with rural and national development goals, typically including improved infrastructure, technological transfer, job opportunities, and financial benefits. However, research and nongovernmental organization reports (12–14) point out that large-scale land acquisitions rarely benefit local people, and that the proposed infrastructure is often not developed on the local scale.

Africa is the continent where most land has been contracted (about 22 million ha) because of cheap land and labor costs (15), but also has the potential to boost yields and reduce yield gaps with modern agricultural techniques and irrigation systems (16). However, many of these land deals have been abandoned or are not yet in production (17), and only about 3% of the contracted deals (0.7 million ha) are currently in production (Dataset S1). These numbers are constantly changing, as land acquisitions are expanding, abandoned, or were never implemented. An example of this is the belief that Chinese investors are major actors acquiring large tracts of land in Africa, which has recently been shown to be on a smaller scale than first reported (18).

The rush for water might be just as important for investors as the rush for land (10, 19, 20). Land contracts rarely indicate any limits to water use, which means that investors might choose inexpensive and inefficient irrigation for their operations. The lack of water regulations thereby increases the risk of unsustainable water use, which in turn has the potential to alter the availability and accessibility for local communities, ecosystems, and other water-intensive sectors.

Human appropriation of freshwater can have vast impacts depending on the management and scale of water use (21), highlighting the importance to estimate the growing water demand associated with land transformations in Africa. No study has yet connected the site-specific water demand to water-use efficiencies of different irrigation systems. This connection is vital because it can indicate areas that might experience increased water stress or conflicts over water resources. The objectives for our study, therefore, are: (*i*) to estimate and identify site-specific green and net blue water demand of crops grown on acquired land in production; (*ii*) to calculate yields, as well as green and gross blue water demand, for crops grown on acquired land under seven irrigation scenarios, and for staple crops as a baseline; and (*iii*) to develop a Blue Water Index (BWI) to identify hotspot areas of increased competition for freshwater resources where demand for blue water exceeds green water supply.

We note that previous continental- to global-scale studies of land acquisitions have met serious critique for issues with data selection biases and quality of data sources, therefore producing results of questionable accuracy (22, 23). One notable example found that 310 $km^3 \cdot y^{-1}$ of green water and 140 $km^3 \cdot y^{-1}$ of blue water are appropriated globally for crop and livestock production (24). However, this study included contracted global land deals, which likely overestimate the water use on acquired land because few projects are currently in production.

As a response to these critiques, and to meet our objectives, we focus on land deals in production. We model green and blue crop water demand with the dynamic agro-ecosystem and hydrology model Lund–Potsdam–Jena managed Land (LPJmL), and provide a clarification of model assumptions and parameterization for the given crops planted. The model output includes: (*i*) green water demand met by rainfall; (*ii*) net blue water demand that plants need to grow, in addition to rainfall; and (*iii*) gross blue water demand that has to be extracted to fulfill plant requirements, accounting for losses between the water source and the field. Water losses depend on the efficiency of irrigation and their distribution systems (see description in Table 1). Finally, we validate the data by cross-referencing the 54 largest land deals in Google Earth, responsible for 95% of acquired land area in production (*SI Materials and Methods*). Because there is a lack of information about water management of acquired land, we model seven different irrigation systems to obtain a full range of plausible water-use efficiency scenarios.

Table 1. The seven different irrigation scenarios that were run with LPJmL for crops planted on large-scale land acquisitions in Africa

Irrigation scenario	Description
Rainfed	Rainfed agriculture (modeled for crops currently in production on acquired land, and for the staple crop baseline)
Drip (pipelines)	Micro (drip) irrigation with pressurized pipelines for distribution
Sprinkler (pipelines)	Irrigation with sprinklers supplied by pressurized pipes
Mixed	Irrigation with a mix of surface and sprinkler irrigation systems with both open canals and pressurized pipes
One-step improvement	Irrigation and distribution systems that are one step higher in efficiency than current national irrigation efficiencies (e.g., moving from sprinkler to drip systems).
Current irrigation efficiencies	Irrigation under current national irrigation and distribution systems in every country (39) (modeled for crops currently in production on acquired land, and for the staple crop baseline)
Surface (open canals)	Surface irrigation systems (flooding) with water diverted from open canals

Scenarios are presented from most (top) to least (bottom) efficient, based on gross blue water use. The current irrigation efficiency, and therefore also the one-step improvement, varies by country.

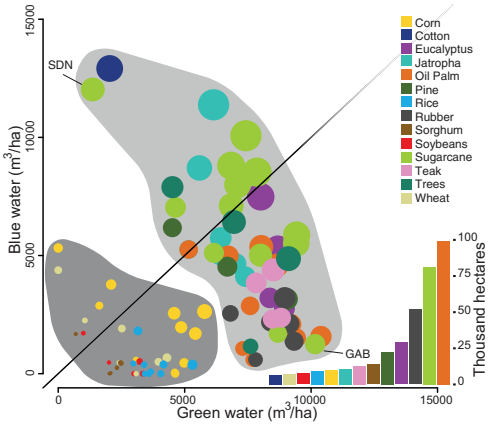

Fig. 1. Average green, net blue, and total water demand ($m^3 \cdot ha^{-1}$) of crops grown on 95% of acquired land currently in production in Africa. The water demand has been averaged to the national level for each crop, the bubbles are scaled to total water demand, and cases mentioned in the main text are labeled with ISO3 country codes (Table S1; for all labels see Fig. S1). The diagonal line indicates where green and blue water demands are equal. Crops are grouped into zones of higher (light gray) and lower (dark gray) water demand. The area of acquired land per crop is shown in the lower right corner, and the largest group "trees" (301,000 ha) has been excluded from the bar chart to see the differences between the other crops.

Results

Land Acquisitions in Africa for Water-Intense Crop Production. More than 60% of the acquired land in production (>418,000 ha) is for forestry purposes (Fig. 1). Most tree species are not specified, but rubber, eucalyptus, pine, and teak are commonly grown for timber or pulp and, in some cases, carbon sequestration (Fig. 1). The next largest crop group is flexible crops, covering 244,000 ha (35% of acquired land). Flexible crops can be used for food, feed, or biofuel; here, these include sugarcane, oil palm, soybean, maize, wheat, sorghum, and cotton. The remaining 5% are acquired for food and beverage crops (tea, coffee, fruits, vegetables), biofuel crops (jatropha), feed, and flowers (Dataset S1).

Our results from LPJmL show that some crops require more water than others (Table S2), but also that the same crop varies in water demand depending on temperature and rainfall. It is possible to distinguish between two crop groups, one with lower water demand (sorghum, soybean, wheat, maize, rice) and one with higher water demand (cotton, eucalyptus, jatropha, oil palm, pine, rubber, sugarcane, teak, trees) (Fig. 1). Within each group, there is a large variation in the amount of green and blue water required to meet the total water demand. For example, sugarcane in the Sudan (green bubble in upper left corner of Fig. 1) has an average net water demand of 13,390 $m^3 \cdot ha^{-1}$ (bubble size) of which 90% is blue water and 10% is green, whereas in Gabon the average net water demand is 15% lower, of which 11% is required from blue water sources and 89% supplied from green water (green bubble in the lower right corner of Fig. 1).

Scenarios for Green and Blue Water Demand and Crop Yields. Simulating water demand with LPJmL enables us to compute water demand of land deals for different irrigation scenarios. Irrigating all land acquisitions has the potential to almost double yields for the crops planted on acquired land (from 17 to 28 megatons) compared with purely rainfed management (Fig. 2 and Table S3). However, this would come at the cost of blue water extractions, which in turn require infrastructure for freshwater appropriation from either local or distant water sources, causing negative impacts on freshwater systems. Total water demand for land acquisitions in production ranges between 5.4 (rainfed) and 8.5 $km^3 \cdot y^{-1}$, depending on the water use efficiency of the irrigation system (Fig. 2). If all land acquisitions were irrigated with the most efficient system (drip irrigation with pressurized pipes), the annual gross blue water use would be 2.1 $km^3 \cdot y^{-1}$, compared with 3.5 $km^3 \cdot y^{-1}$ if the least-efficient irrigation system (surface irrigation with open canals) were used, leading to a water efficiency improvement of up to 40%.

Producing maximum crop yield (Fig. 2) requires less water for all irrigated cases, ranging from 255 m^3 of water per ton of crop yield for drip irrigation, to 300 $m^3 \cdot ton^{-1}$ for open canal surface irrigation, compared with 315 $m^3 \cdot ton^{-1}$ for rainfed agriculture (Fig. 2 and Table S3). This means that establishing irrigated agriculture in areas of production would demand more water in total, but require less water per unit of production compared with the rainfed case.

To estimate the added pressure on water resources by land acquisitions compared with previous land use, we provide a baseline of water demand for five staple crops widely grown under small-scale farming systems in the affected countries: maize, wheat, rice, sorghum, and cassava (Dataset S2). We model the most common staple crops grown in that country, at the location of the acquired land, using both rainfed and national irrigation efficiency scenarios for the year 2000. The water requirements for staple crops varies between 2,500 and 14,500 $m^3 \cdot ha^{-1}$ (average 5,500 $m^3 \cdot ha^{-1}$), summing up to a total green water use of 3.3 $km^3 \cdot y^{-1}$ under rainfed conditions, with an additional 0.5 km^3 of blue water if the staple crops were irrigated with national irrigation efficiencies (Table S3). This finding suggests that green and blue water use is 39% and 76–86% greater, respectively, for crops grown on acquired land compared with the baseline of common staple crops, showing that land acquisitions substantially increase water demands.

Mapping Blue Water Use Hotspots with the BWI. To assess what areas might face increased water scarcity as a result of land acquisitions, we relate crop water demand to the water supply of the specific area in production by calculating the ratio between the gross blue water demand to the total (green + gross blue water) water demand for these crops. We call this the Blue Water Index, which indicates the fraction of water added from irrigation needed to generate maximum yields. An index of 1 indicates that all crop water comes from irrigation, whereas an index of 0 indicates that precipitation is sufficient to achieve maximum yields. The BWI helps identify those land acquisitions that might have large impacts on freshwater availability.

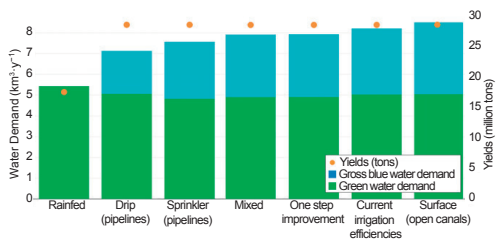

Fig. 2. Total yields for current crops (tons, orange dots, *Right* axis) and green and gross blue water demand ($km^3 \cdot y^{-1}$, *Left* axis) for 121 large-scale land acquisitions in production in Africa for seven irrigation scenarios (Table 1). Local estimates for each deal have been aggregated to a continental scale for each irrigation scenario shown in increasing efficiency. In all cases, irrigation nearly doubles crop production from the rainfed scenario, but at the cost of 2.1–3.5 km^{-3} of blue water per year, a variation within irrigation systems of 40%.

For all irrigation scenarios, land acquisitions in production with a BWI lower than 0.5 (less than 50% of water demand from blue water sources) are distributed in tropical and temperate climate zones of sub-Saharan Africa (Fig. 3 and Dataset S3), whereas land acquisitions with a BWI above 0.5 (more than 50% of water demand from blue water sources) are scattered throughout all climate zones from dry to tropical (Fig. 3).

These blue water hotspots are mapped in Fig. 4, which shows the effect of irrigation system on blue water use. Under current national irrigation efficiencies, 35% of all land deals in production would be hotspots (Dataset S3), with 33 land deals using 50–75% blue water and 9 using >75%. The remaining 46 deals using 25–50% blue water and 33 deals using <25% (Dataset S3) may still stress local water systems. If more efficient sprinkler or drip irrigation were applied, hotspot areas would drop to 22% and 18% of total deals in production, respectively (red and yellow dots in Fig. 4). Even under the most efficient drip irrigation system, there will still be 22 land acquisitions where more than 50% of water would be drawn from blue water sources to meet demand, most in Central and Eastern Africa (red dots in Fig. 4).

Discussion

Water Intense Crop Production of African Land Acquisitions. As shown in this study, most acquired land in production is for forestry and flexible crop production for crops with high water demand (e.g., sugarcane, jatropha, trees, and eucalyptus). It is relevant to consider site-specific green and blue water demands of individual land acquisitions to identify land deals that might induce water stress, and cause water-related conflicts between different water users. Blue water demand depends on crop choice and location. From a water-efficiency perspective, for example, it is better to grow sugarcane in the Congo than in the Central African Republic, but in the context of food security it might be better to develop the land for food crops that require less water, like maize, rice, sorghum, and wheat (shown in the light gray zone in Fig. 2). However, in reality, low water demand is not the primary driver of crop choice, but rather local to global demand, market prices, and nutrient calorie content play more dominant roles in deciding crop production (25).

Scenarios for Green and Blue Water Demand. Green water demand from crops now planted on acquired land (5.4 $km^3 \cdot y^{-1}$) is substantially higher than it would be for traditional staple crops (3.3 $km^3 \cdot y^{-1}$). It is important to consider the scale of production when calculating blue water use, and to assess how blue water demands differ depending on the irrigation system implemented. Irrigating all crops currently in production for land acquisitions on a continental scale would require 2.1–3.5 km^3 of blue water per year in addition to what is supplied naturally from rainfall. By adding this amount of blue water, it is possible to maximize and almost double yields compared with rainfed agriculture. It is reasonable to assume that investors irrigate acquired land because they want to guarantee high agricultural productivity and reduce the risk of crop failure because of erratic rainfall (10). Land acquisitions in semiarid regions are, however, more likely to be irrigated than in tropical regions, as a result of crop type and relative availability of green water. Note that this is accounted for in LPJmL, as blue water requirements are only added if needed to avoid soil water deficit.

Improving water-use efficiency, while also considering the purpose of production (food, feed, or fuel) and the location of consumption, is essential for developing more sustainable agricultural systems. Efficiently irrigated agriculture contributes to increased yields and also allows allocation of water to other sectors, like sanitation and health, but for already water-scarce regions, the additional extraction of blue water might be substantial even if the most efficient irrigation system is implemented. If water is available and free of charge, investors will probably prefer cheap and inefficient irrigation systems, such as surface irrigation ($600–800/ha) or sprinklers ($3,000–5,000/ha) rather than expensive but efficient drip irrigation systems ($10,000/ha) (26). In reality, the irrigation scenarios are linked to factors like economic costs, labor

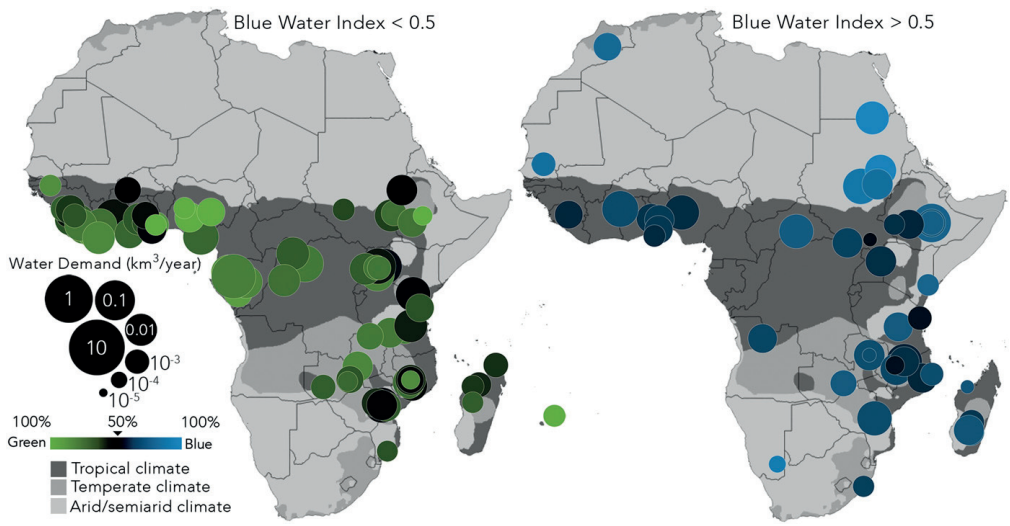

Fig. 3. Individual land acquisitions with a BWI less than 50% (*Left*, 79 land deals now in production where the majority of water demand is met by precipitation), and land acquisitions with a BWI greater than 50% (*Right*, 42 land deals where the majority of water demand would be extracted from irrigation). The BWI in this figure is based on the current national irrigation efficiency scenario (39) for crops grown there.

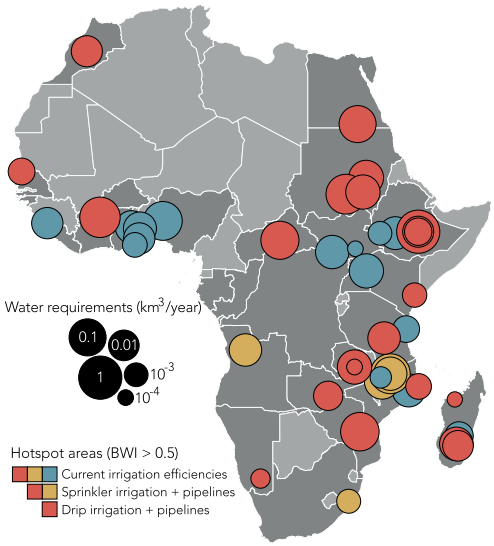

Fig. 4. "Hotspot" land acquisitions in production (countries in dark gray) where blue water use is more than 50% of crop demand across three different irrigation scenarios: drip irrigation (red, 22 locations), sprinkler irrigation (yellow, an additional 5 locations beyond the drip irrigation locations), and current irrigation efficiencies (blue, an additional 15 locations beyond the drip and sprinkler locations). The size of the circles indicates the total water demand (green + gross blue). These land deals have been highlighted to identify hotspot areas that might experience increased competition between sectors over freshwater resources.

intensities, water rights, and governance. However, these factors could not be considered in the present biophysical framework, where our goal was to bracket the range in water use given a variety of irrigation scenarios.

Blue Water-Use Hotspots. The BWI was developed to delineate hotspot areas of blue water demand, and to indicate areas where increased freshwater use potentially creates tensions and conflicts between different water users. We find that 22% of land acquisitions in production (for the sprinkler irrigation scenario) require more than 50% of their water from blue water sources. Land acquisitions with a BWI above 0.5 are scattered over all climate zones, from dry to tropical, which indicates that it is not only the lack of rainfall that gives rise to water-scarcity hotspots, but also crop choice and scale of production. For example, both West Africa and Madagascar are tropical zones where there are land deals with both high and low BWI.

Beyond Water. Just because a crop planted on acquired land is suitable to grow in that area does not mean that the area is suitable for large-scale agriculture. There are several other risks to be considered, including biodiversity loss from land conversion, and loss of land-rights for people who are engaged in small-scale farming (among others). For example, Central Africa has the second-largest rainforest in the world and is rich in biodiversity (27). Until recently, forests there have remained largely intact because of low demographic pressure and limited accessibility (28), but deforestation has increased in recent years as a result of the rush for farmland (29). Consequently, large areas of forests and people's access to land are threatened (30).

Many investors claim to stimulate local and national development, thereby reducing rural poverty and food insecurity (11, 25); however, optimizing yields for timber or biofuel crops for export might not be the most suitable option to do so (31). Even though socioeconomic benefits in terms of infrastructure and employment might contribute to food security on the local scale (25), case studies have found that this has not been realized on the ground (32, 33). Therefore, there is a need to further examine local implications for rural societies and ecosystems, and whether the crop production is of benefit to the national or local population. This approach would shed light on the trade-offs between the purpose of production and increased yields at the cost of ecosystem health (e.g., water pollution, reduction of wildlife, and deforestation), as well as local to national socioeconomic trade-offs regarding infrastructure development and employment.

Data Limitations and Key Assumptions. There are several data limitations for the land deals themselves, as well as current water management in the study area. Although Land Matrix is the most extensive dataset currently available, it is continuously being updated as a result of the rapidly changing nature of the land deals, highlighting issues of uncertainty (34, 35). Nevertheless, these data are suitable for showing general trends and patterns.

Additionally, there is a lack of information about water management for current land deals, which is why we modeled different irrigation scenarios. To refine this measure, there is a need for additional research on the types of irrigation systems that are implemented, the source of blue water, as well as on how the water is diverted to the irrigation system. It is also a challenge to estimate the added pressure on freshwater use by land acquisitions, because there is a lack of data about previous land use. This is a research gap that needs to be filled to assess changes in water use with greater confidence.

This study is an estimate of how much water the plantations on acquired land might require for different types of irrigation systems. We assume (using LPJmL) that irrigation requirements can always be met. This assumption is reasonable, given the additional assumption that investors are likely to assess the availability of water (and potential for profit) associated with leasing or purchasing land. It is worth noting that the aggregate figures of land and water use from land acquisitions are likely to be an underestimate because of the conservative assumptions made in this analysis.

Finally, crops that are not specifically parameterized in LPJmL were modeled as crops with similar behavior (*SI Materials and Methods*). The class "managed grasslands" was used as a proxy for 21 crops covering 31% of acquired land (Table S4). Although uncertainties introduced by this procedure may be low for crops like alfalfa, uncertainties will be higher for tree crops. Consequently, estimates for water use and crop production should be treated with care for these crops. Future model development should focus on parameterizing the most widespread crops not currently in LPJmL: oil palm (14.3% of planted area) and rubber (7.5% of planted area).

Conclusions

Our study quantifies water demand of land acquisitions in Africa as a function of crop choice, local climate, and irrigation scenarios. As such, it advances the field by detailing the implications of crop choice and irrigation techniques on water demand. It also highlights areas that might experience conflicts and tensions over freshwater use between sectors, especially hotspots using more than 50% blue water for crop production.

We show that there is potential to boost yields through irrigation, but that blue water demand varies with irrigation system (because of water use efficiencies). Even if the most efficient irrigation system is used for land acquisitions in production, 18% would require more than 50% of water from blue water sources. If land acquisitions are to benefit local communities, investors

need to re-evaluate the purpose of production together with local decision makers and communities while also considering crop water demand to minimize negative trade-offs between water users and ecosystems.

Materials and Methods

Data on Land Acquisitions. We used the collection of large-scale (>200 ha) land deals from Land Matrix (Retrieved in July 2014; www.landmatrix.org/en/). The Land Matrix database contained a total of 1,795 land-deals with an emphasis on food, fuel, and forestry crops. Of these, 747 deals were contracted in Africa, of which 121 were currently in production (Dataset S1). The dataset has geographical coordinates for each specific deal. We cross-referenced the Land Matrix data by observing the 54 largest land acquisitions in Google Earth, representing 95% of acquired land area (Fig. S2).

Simulation of Agricultural Production and Water Demand with LPJmL. There is no information about the irrigation systems the investors use in the existing datasets, prompting the use of the LPJmL (36, 37) to estimate the green and blue water demand for seven different irrigation scenarios, at the site-specific locations given by land-deal coordinates. All scenarios include simulations of vegetation growth, phenology, and agricultural yield (*SI Materials and Methods*).

For LPJmL simulations, we assume that deals are managed intensively; that is, efficient pest and disease control, high-yielding varieties, mechanization, homogenous fields, and no nutrient limitations (see ref. 38 for details on the management parameters). Second, we assume that irrigation water is always available in the irrigated scenarios, if not locally, then by developing water infrastructure that would divert water from local or nonlocal sources. Finally, many crops that are grown on acquired land in Africa were not specifically parameterized. Instead, they were simulated by using a proxy crop with similar characteristics (*SI Materials and Methods*).

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Paper III

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Research, part of a Special Feature on Reconciling Art and Science for Sustainability

Local perceptions of land-use change: using participatory art to reveal direct and indirect socioenvironmental effects of land acquisitions in Kilombero Valley, Tanzania

Emma L. Johansson [1] *and Ellinor Isgren* [2]

ABSTRACT. In this study, we combine conventional qualitative approaches with a more novel approach, participatory art, to explore local perceptions of land-use change and future aspirations for development in two communities in Kilombero Valley, Tanzania. We concentrate on the effects of large-scale land acquisitions on people and the environment in an ecologically important area. Leasing of land to foreign agribusinesses for the production of timber, food, and fuel crops has created a politically charged debate with strong ideologies on both sides, and people directly impacted are not the ones driving the debate. Local farmers, fishermen, and pastoralists were cued about landscape and livelihood changes through focus-group discussions, interviews, and by cocreating paintings of the past, present, and future. Findings reveal that art can make a valuable methodological contribution for understanding and communicating complex interactions between drivers of change and their socioenvironmental impacts, and for exploring desirable future visions.

Key Words: *land grabbing; land-use change; large-scale land acquisitions; participatory art*

INTRODUCTION

In recent decades, we have witnessed an escalation of sustainability challenges across the world that impact people and the environment in different ways, including climate change, water scarcity, natural disasters, inequality, and resource conflicts (Kates and Parris 2003). Land-use and land-cover change are both drivers and solutions to many of these challenges. Land-use change is a key processes by which humans influence the functioning of the Earth system, contributing to environmental change and in turn affecting people (Turner et al. 2007, Lambin and Meyfroidt 2011). Particularly vulnerable are people who are poor and live directly off the land as small-scale farmers, but these groups often have little power to influence decisions affecting their society and surrounding environment (Bryant 1998). About 80% of the population in Tanzania reside in rural areas and depend on agriculture for their livelihoods, making the availability and accessibility of land very important (Mombo 2011). In recent years, there has been a rise in foreign direct investment in agricultural land, often seen as part of the "global land grab" (Zoomers 2010). In this paper, we respond to the call for more participatory methodological approaches for better understanding effects of large-scale land acquisitions (Scoones et al. 2013). The aim of this research is to focus on perceptions and lived experiences of land-use change within communities in Kilombero Valley, where foreign agribusinesses have acquired land, and thus contribute to the wider debate on how large-scale land acquisitions can be understood from a bottom-up perspective. In order to achieve this aim, we address the following questions: (1) what are the local perceptions of socioenvironmental change, and what is the role of large-scale land acquisitions? (2) What is the usefulness of participatory art as a method to facilitate discussions and visualize socioenvironmental change and future aspirations within communities where land is leased?

This article is structured into five sections. In the introduction, we elaborate on the issue of large-scale land acquisitions, particularly in Tanzania, why local participation is needed in knowledge production about their socioenvironmental impacts, and the potential value of introducing new methodological tools such as art. The next section provides a description of the fieldwork area. In the third part, we describe the methods used in the fieldwork; the fourth section synthesizes the findings from the two different sites. In the fifth section, we discuss and reflect on both the findings and the methodological approach. Finally, we offer some concluding remarks and suggestions for future research.

Large-scale land acquisitions as a driver of land-use change

Large-scale agroindustrial expansion is now a dominant driver of land-use change, and the demand for agricultural products is expected to increase by 50% by 2050 (Gibbs et al. 2010). Agriculture is also the biggest freshwater user, responsible for 70% of global freshwater withdrawals (Shiklomanov 2000). Environmental impacts from agriculture range from local to global and include losses in carbon storage, wildlife habitat, and degradation of watersheds (Gibbs et al. 2010). This has negative implications for biogeochemical and biophysical climate regulation, as well as for people who critically depend on terrestrial and aquatic ecosystems for food and freshwater provision (Foley et al. 2005).

Tanzania is one among many African countries experiencing renewed interest in large-scale investment in agricultural land (Nelson et al. 2012). The Tanzanian government has played an active role in attracting such investments for a long time (Alden Wily 2012), and land contracts of 33, 66, or 99 years have been given to transnational and domestic large-scale agribusinesses to grow cash crops like sugarcane, rice, maize, vegetables, and various high-value tree crops (Locher and Sulle 2013).

Following the intensified commercial interest in agricultural land, there has been a surge of research into its geography, scale, drivers, and impacts. Also, public media and civil society organizations have taken part in the debate, which has come to be highly polarized (Cotula et al. 2014). Should large-scale investments be

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welcomed because they can assist transition toward more modern and productive agriculture, or should they be curbed because they represent nothing more than "neocolonial theft" of local livelihoods without significantly contributing to national economic development (Toft 2013)? Many scholars have called for more research on the impacts of land deals within national and local contexts to create a stronger basis for decision making around them (Borras et al. 2011, Hunsberger et al. 2015). However, assessing impacts of land acquisitions is notoriously difficult; there is often a lack of reliable baselines, impacts are socially heterogeneous and change over time, and they interact with other pressures on land (Cotula et al. 2014, Oya 2013). Scoones et al. (2013) warn that the "literature rush" that has accompanied the "land rush" has led to a bigger but not always better picture of the phenomenon. They argue that the problem is methodological, agreeing with Edelman (2013) that research has been overly "hectare-centric," and call for a second phase of research that favors more grounded and specific approaches. Aggregate measures of the extent and patterns of land trade and well-designed quantitative surveys of their impacts are undoubtedly important, but there is a need to complement these with participatory approaches that allow researchers to become "conduits for local voices rather than replacing them" (Scoones et al. 2013: 479).

Local participation in knowledge production about land acquisitions

Although a substantial body of scholarly work around large-scale land acquisitions has emerged, people actually affected rarely determine the focus of research, and the most pressing socioenvironmental issues in particular locations may get overlooked. Furthermore, when focusing solely on the mechanisms and impacts of investments—which are also important—the question of alternative approaches to agricultural development beyond foreign investment in large-scale projects gets overlooked (de Schutter 2011). This also applies to appropriate responses and desirable alternatives from the perspectives of impacted communities once foreign companies are in place. When pathways to sustainability are understood as multiple and place specific, research needs to span spatial and temporal scales to reflect the complexity in human and natural interactions. There is a need to recognize the wide range of perceptions and preferences of relevant societal actors, not least those who are most impacted by, and vulnerable to, social and environmental change (Schneider and Rist 2013). This also necessitates "decolonizing" research to reduce the power imbalance in knowledge production (Cook 2015), especially when there are large cultural differences between researchers and the researched. Through innovative participatory methodologies, many aspects can be included that otherwise would not be considered by the researcher, such as local forms of knowledge and normative values (Swart et al. 2004). Indigenous observations can strengthen land-change research as a rich source of environmental history and as a framework for formulating research questions because they provide a valuable opportunity to uncover local concerns (Nightingale 2003, Carothers et al. 2014). Participatory methodologies have thereby been argued to be empowering, for example by legitimizing local knowledge, involving marginalized groups in joint learning processes, and drawing attention to issues affecting them (Chambers 1994, Enfors et al. 2008).

Much conventional research involves some form of "participation." What sets apart explicitly "participatory" research, Cornwall and Jewkes (1995) argue, is the ambition to shift the location of power in the research process. In part a response to reductionist scientific approaches, participatory research also acknowledges the complexity of local situations and knowledge gained through everyday life (Glassman and Erdem 2014, Brydon-Miller et al. 2003, Gaventa and Cornwall 2006). Participatory approaches are found in many academic disciplines, especially within development and sustainability research (Lang et al. 2012, Brandt et al. 2013). In the context of socioenvironmental change, participation can increase affected people's ability to influence knowledge generation and decision making and to insert their knowledge into the public discourse (Cook 2015). More an "attitude or approach" than a series of techniques, participatory research often seeks to expand the repertoire of research activities to include different forms of art and storytelling, often in combination with more conventional methods (Cornwall and Jewkes 1995). Participation can be brought about in a wide variety of ways, with different purposes, agendas, and implications. This research approach is certainly not without problems and pitfalls, requiring a high degree of reflexivity (Pain and Francis 2003).

Art in participatory research

Art and science both attempt to capture the world around us in creative and innovative ways to create novel knowledge and awareness. Integrating arts into research can be a way to synthesize complex issues, improve communication, and construct new integrative narratives by engaging audiences from different cultural contexts (Curtis 2011, Heras and Tàbara 2014, Streck 2014). The use of art in research is often discussed as a matter of finding new ways to close the gap between awareness and behavior, as art has the potential to emotionally, intuitively, and cognitively evoke change and thus "speed up" sustainable societal transformation, as hypothesized by Heras and Tàbara (2014). But creating art through collaborative processes is also a way to elicit knowledge, values, and emotions, a central objective of qualitative research. As a methodology, participatory art can provide a platform for discussion and a "shared space," which is more familiar to many people than conventional research activities (Zurba and Berkes 2013). Although the process is as important as the product, the material outcome can form a "boundary object" that takes on different meanings for different actors (researcher, participants, viewers) but facilitates communication between them (Star and Griesemer 1989). Furthermore, visual art is useful for creating future visions, which are increasingly used in order to explore socioenvironmental effects of human-induced land-use change, such as trade-offs between ecosystem services and human wellbeing (Palomo et al. 2011, Hanspach et al. 2014, Oteros-Rozas et al. 2015). A vision is a type of scenario that describes desirable future states without making predictions. Visioning can stimulate creative thinking about the future and is often combined with stakeholder involvement, for instance to take into account local people's knowledge and preferences, and identify possible pathways to reach that future (Schneider and Rist 2013, Wiek and Iwaniec 2014).

To sum up, land-use change associated with large-scale land acquisition is an area of research that would benefit from methodological expansion toward novel qualitative and participatory approaches, as it (1) allows people who are affected yet underrepresented to influence the research focus and uncover local concerns that can be further researched, (2) creates a platform to explore desirable alternatives and preferences expressed by the people in place, and (3) helps to understand and communicate the complexity of situated human–nature interactions and lived experiences by people who are dependent on and vulnerable to (but could also benefit from) social and environmental change. Joint production of visual art is one possible way of complementing conventional research methods as it enriches discussions and communication both during and after fieldwork. Participatory art workshops were used in this study as a means to explore how people perceive the past, present, and future in relation to socioenvironmental change.

METHODS

The fieldwork is exploratory and participatory both in its aim and design and is inspired by methods from ethnography and participatory rural appraisal (Chambers 1994). The fieldwork decisions were made in collaboration with people in Tanzania, with the initial criteria that the case-study areas should experience land-use change due to large-scale land acquisitions and that the companies should be in operation (not in the start-up phase or abandoned). The ultimate aim was to let people in communities adjacent to land acquisitions share their perceptions of land-use change and guide the focus of the research toward issues that are of concern for them, within the domain of environmental change and human–nature interactions. This exploratory approach can strengthen research as a framework for formulating research questions that are based on local concerns and conditions (Carothers et al. 2014).

Study area

The fieldwork was done in March to May 2015 in Kilombero Valley, Tanzania, in villages where transnational agribusinesses have acquired land within their village boundaries. The site was chosen because of the rapidly increasing pressure on natural resources due to a rising transnational and national interest to convert land into large-scale agriculture and timber production. Kilombero Valley is referred to as the Breadbasket of East Africa due to its ideal conditions for agriculture with year-round warm temperatures, fertile soils, and abundance of water (Mombo et al. 2011). It is a biodiversity hotspot and has one of the largest freshwater wetlands in East Africa (Kangalaweand Liwenga 2005*b*). There is a growing international interest to protect the biodiversity of Kilombero Valley, and the floodplain was declared as a Ramsar site in 2002 and is thereby protected under the Convention on Wetlands of International Importance. The wetlands are important for indigenous communities who traditionally use the land for farming (common crops include rice, maize, oil palm, banana), fishing, and grazing (Kangalawe and Liwenga 2005*a*).

The fieldwork was conducted in two case-study areas, located in the Kilombero and Ulanga Districts. In the first site, Kilombero Plantations Limited (KPL) have acquired 5800 ha of land since 2007 with a 99-year contract for rice production. In the second site, Kilombero Valley Teak Company (KVTC) have acquired land since 1992 and currently have a 99-year contract for teak production on 28,132 ha of land. KVTC is planting around 8000 ha of the acquired land with teak because the remaining valley land and highland are not suitable for teak production.

Focus-group discussions

Focus group discussions were held in five villages (three for KPL and two for KVTC) in order to get an initial overview of the area and of different people's perceptions of environmental change. The focus groups deliberately included farmers, fishermen, and pastoralists, young and old, men and women. Fishermen and pastoralists are often also engaged in farming. The questions were open ended in order to cocreate a narrative about how natural resources have changed, reasons for change, and how different livelihood practices are affected by the environmental change; furthermore, we cued about future aspirations for development. Following this, additional focus-group discussions were held with fishermen and pastoralists because they were underrepresented later on in the painting process due to distance and time constraints. The focus-group discussions formed the basis for the painting workshops in that they provided the main concerns and stories of change. In total, seven focus-group discussions were held: five with mixed participants, one with pastoralists, and one with fishermen.

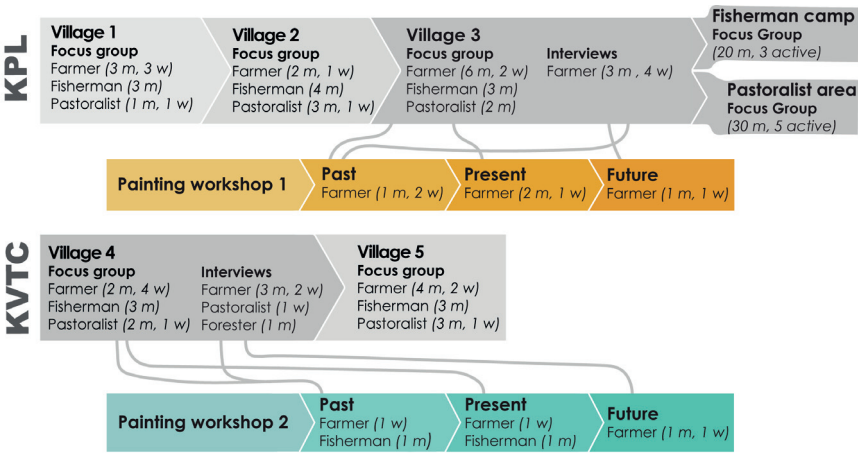
Painting workshops

We arranged painting workshops in two villages, one that leases land to KPL and one to KVTC. The first workshop was held in the village where most land has been acquired by KPL, whereas the second village was chosen according to what was most practical regarding distance, time, and accessibility (KVTC). In each village, we made three paintings, representing the past, present, and future. The paintings were made outside the village office, and each painting took around 4 d to complete, providing plenty of opportunities to discuss the process, content, and issues being painted—both with participants and with community members passing by.

The participants in the painting workshops (one woman and one man per painting) were selected from the focus groups based on interest and availability. If no focus-group members could participate, we asked a woman or man of a certain age, depending on who was underrepresented (Fig. 1). These participants were interviewed and informed about the general outcomes of the previous focus-group discussion. At first, the aim was to have three participants per painting, representing all livelihood groups. However, because of the distance to the center of the village, it was difficult for pastoralists and fishermen to participate beyond the focus groups. Although these livelihood groups were represented in the paintings—as the focus groups formed the basis of the painting workshop—there is a risk that their perceptions might be less emphasized.

Inspiration for the paintings was drawn from the Tanzanian art style "tinga-tinga," a common art style with roots in African tradition that generally has storytelling motives of animals and people in a Tanzanian environment. This style was chosen because of its familiarity and because of its ability to capture human activities and interaction with natural resources. The role of the artist was to instruct the participants how to paint and to make decisions on the aesthetics, but with input from the participants on how the different elements should look. The role of the

Fig. 1. The methodological process for the two case-study areas, showing the livelihood and gender (male (m), female (f)) distribution of the participants of focus-group discussions and interviews. The figure also highlights which focus groups formed the basis for the two painting workshops and if participants were previously part of the focus group or included through interviews.



researcher was to facilitate discussions and storytelling, but also to take part of the painting process and ensure that all participants were equally included. Based on the focus-group discussions, the participants were asked to explain and visualize: (1) How their village and surrounding environment currently is affected by land use, in terms of natural resources and human activities. (2) How their village and surrounding environment was before land was acquired in the village, in terms of natural resources and human activities. (3) What future aspirations they have for their village and surrounding environment, in terms of natural resources and human activities.

This focus on three different time periods is a means to capture how people perceive and experience changes in their environment, including the relationship between community and land use. In the following sections, we will explain, in general terms, how the paintings were made.

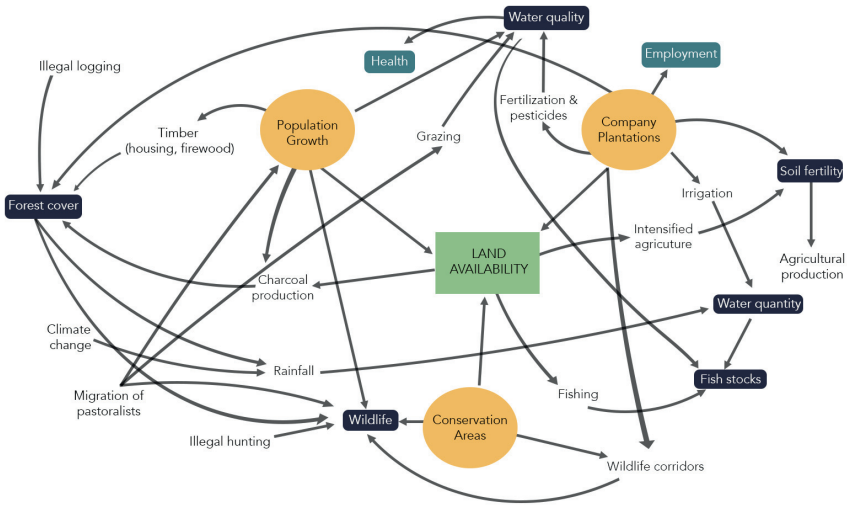
Painting process

We started by painting the present, serving as a baseline for describing the past and thinking about the future (e.g., more/less, better/worse). The process began by the artist and participants making a sketch on paper of where things are located in relation to each other: e.g., mountains, rivers, main roads, settlements, company site, grazing areas, and wetlands. Then we transferred the sketch to the canvas to paint how the environment looks today, to finally add the human activities and stories about interactions between the company, community, and environment. The motif was based on what was brought up during the focus-group discussions, but people that passed by the village office (where we were painting) also added, edited, and confirmed stories in the painting. The next step of the workshop was to paint the past. We agreed that the past should represent the time just before the foreign company acquired land in the village. As the first village has a history of many companies, we agreed to focus on the time just before the arrival of KPL. Two older people participated in painting the past because they have a better idea about the past than the youth. The same landscape was painted, but now rivers, forest, and settlements were resized and replaced in relation to the current situation and location. Human activities were also painted in relation to the current situation in order to visualize the changes for different livelihoods. Finally, we made a painting of future aspirations, and for this painting, two young farmers participated. As none of these participants had been part of the previous focus-group discussion, we informed them about what had been said and also encouraged them to ask other people about how they want the future to develop in order to spur their imagination.

Observations and additional interviews

Both villages were observed and explored by foot, bicycle, and motorbike, which allowed easy access to various locations in order to get acquainted with the environment, meet people to observe and learn about how they live and use the land and other natural resources. Additionally, during the 2–3 weeks in each village, open-ended interviews were held with stakeholders that in various ways are engaged in development and land-use change of the Kilombero Valley (company employees, research institutes, district ministries, NGOs). The purpose of engaging with actors outside the village boundaries was to get an overview of how focus-group participants' perceptions about patterns and processes compare with the perceptions among people who work with wetland protection, large-scale agriculture, and Kilombero district administration. This was not an attempt to validate or reject local perceptions, but rather to deepen our analysis of how these can be used to understand socioenvironmental change.

Fig. 2. General schematic of common features identified in both case-study areas regarding how land use is impacted and impacting on the environment and human wellbeing due to the higher pressure on land. The green square is the central part of the analysis, representing land availability for livelihoods. The yellow circles are the main pressures that affect land availability. The noncolored words are processes that are changing the state of the environment (dark blue) and people's "wellbeing" (light blue) as an effect of the increased pressure on land.



Analyzing and synthesizing the material

Analysis began during fieldwork when information from the focus-group discussions was translated into paintings, and the paintings in turn were viewed, explained, and discussed. In this way, participants not only contributed with data but also took part of interpreting it. After fieldwork, analysis was continued using audio recordings, notes, and the paintings. The focus was to identify how the use of land in the study areas has changed over time, and with what social and environmental impacts. In the presentation of findings, we display the paintings alongside a synthesized textual narrative and a generalized schematic of how different socioenvironmental processes affect natural resources. The schematic aims to introduce the reader to dominant processes and outcomes that can be generalized from both sites. The figures of the future paintings contain numbers in order to more easily connect the visualized objects with the textual narrative as these objects tend to be more symbolic representations of change than the paintings of the past and present.

RESULTS

Overview

The outcome of the focus-group discussions, interviews, and painting workshops shows that, in both cases, local communities have experienced an increased pressure on land and water resources during the past decades. Figure 2 synthesizes and illustrates the dominant pressures and processes as explained by the people participating in the discussions. Multiple causes of change were pointed out, including population growth, in-migration of people and cattle, increase of nature conservation areas, and large-scale transnational and domestic agricultural businesses. These pressures have been exacerbated by climatological challenges like higher frequency of droughts. The increased pressure on land and water changes the availability and accessibility of natural resources for local communities, thus creating new socioeconomic challenges, as few local residents have been able to find satisfactory alternatives to their traditional livelihoods of farming, fishing, and animal husbandry.

Visualizing the change from past to present

The paintings of the past and the present point to environmental changes, including deforestation, decreased water availability (and fish stock) in rivers, reduced wildlife, and decreased land available for farming (Figs. 3, 4). The participants traced these changes to both land acquisitions and population growth. Population growth was consistently described as the main driver of increased pressure on natural resources, both from a high natural growth rate, but also due to rapid in-migration of pastoralists during the last decade. This falls in line with census data that show that Kilombero and Ulanga Districts have experienced a 24% and 26% growth, respectively, in rural population from 2002 to 2012 (National Bureau of Statistics (NBST) 2012). The presence of the companies has had both direct and indirect effects on natural resources. Direct effects include reduced water levels in rivers due to irrigation or introduction of tree species with high water requirements. Indirect effects include

deforestation and lower fish stocks in the rivers because people have lost access to land where they used to farm (causing them to shift to fishing), swamps where they used to fish, and shrublands where they fetched firewood. The participants further believe that deforestation affects the rainfall patterns and contributes to lower water levels in the rivers. The reduction of wildlife is seen as an effect of company interference with previous habitats and migration routes, as well as expansion of farming areas and village settlements to the wetland area (due to population growth and land leased to the company). Similar observations were made by Rovero and Jones (2012), who found that the main migration route between the Udzungwa Mountains and Selous game reserve has lost connectivity during the last decade and became closed in 2010. They suggest that the main causes of disruption are increased cattle, high human immigration into the corridor area, and conversion of land to farming and grazing.

Fig. 3. The paintings of the past (top) and present (bottom) situation of Mkangawalo Village, where KPL is growing and processing rice. The past represents about 10 years ago. The main changes seen in the paintings are reductions in forest cover, water quantity, and number of wildlife; an increased population and migration of pastoralists and cattle; and a shift of farms and settlements to the wetlands due to the reduced land availability caused by the agribusiness.

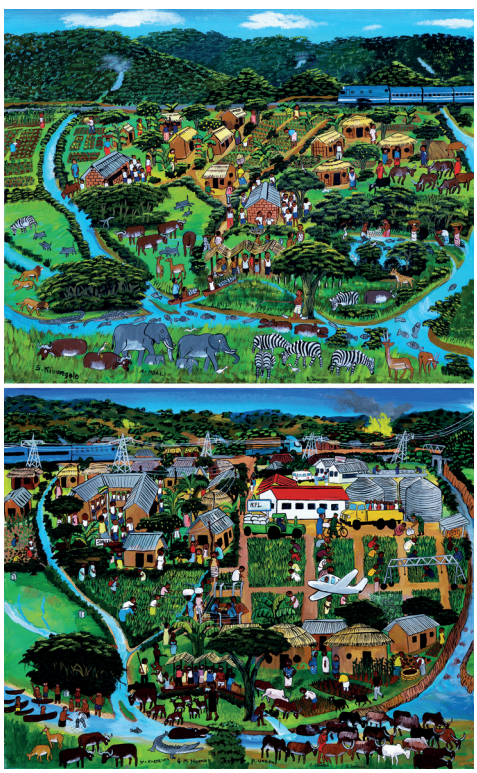


Fig. 4. The paintings of the past (top) and present (bottom) situation of Nakafulu Village, where KVTC is growing teak trees in the uplands. The past represents about 30 years ago. The main changes seen in the paintings are the reductions in natural forest cover (replaced with teak trees), water quantity, wildlife numbers, and yields; an increased population and migration of pastoralists; and an expansion of rice fields to the wetland area.

The societal changes described by participants refer to how people use the land and how they are affected by environmental change and the presence of the companies. The dominant stories relate to reduced access to farmlands, accusations and punishment for stealing from the company plantations, as well as negative impacts on health and crop yields. Accessibility of farmlands has decreased for multiple reasons: Firstly, the village rice fields have expanded due to population growth. Secondly, land leases have influenced the location of village rice fields. In the case of KPL, the company's arrival has forced a shift toward the Ramsar wetland area that is distant from the permanent settlements. In the case of KVTC, the lease prevents farmers from expanding

their fields into areas that they would prefer for rice production. Here, participants expressed that if they had known how much population in the area would grow, they would not have given up this land at the time when the company arrived. Thirdly, the roads and paths to access these areas have been cut off by company roads and ditches that local people are not allowed to use. In the case of KPL, this ties in with the stories about accusations of theft, as farmers use the company roads to carry rice from the distant fields to the village center. When doing so, company guards accuse them of stealing rice (which also occurs), confiscate their harvest, and sometimes beat them. Impacts on health and yields are mainly believed to be caused by the spread of pesticides, herbicides, and fertilizers by aircraft in the case of KPL, but also due to the belief that the teak trees, in the case of KVTC, drain the soils of water and nutrients. One of the participants also mentioned that the pollinating insect species have changed since teak trees were introduced in the area, suggesting that this also may have reduced yields of rice and maize. This is not likely to be the reason for declining yields as these crops are wind pollinated (McGregor 1976), but could, however, be the case for crops like beans, cotton, peanuts, and soybeans that benefit from insect pollination. Finally, community members are dissatisfied with the low wages and insecure employment offered by the companies (seasonal employment involving planting, weeding, and harvesting), but few see any other alternatives than to work for them. The low wages (e.g., $2 a day for KPL) is not a sufficient alternative to small-scale farming or fishing, but many see no other option than to accept temporary employment as farming is more challenging due to the increased pressures on land and water.

The future

As visualized in the paintings (Figs. 5, 6), participants from the two communities share similar future aspirations in the form of infrastructure development, restoration of natural resources, and increased participation and authority over company decisions. The last point is, in both cases, illustrated with a mango tree where local community members can openly meet with company representatives (number 1 in Figs. 5 and 6). Desired infrastructure improvements include paved roads, access to electricity, and improved houses. They also show that farmers want some mechanization of agriculture through the use of tractors. To reduce the impacts on water bodies, the participants suggest that KVTC should increase the buffer zone and replant native tree species along rivers (number 3 in Fig. 6). For KPL, most community members want the irrigation to stop (number 3 in Fig. 5), but the opinions differ, and some participants say that the company should maintain irrigation at the current level or even increase irrigation. In the village that leases land to KPL, people want illegal fishing to stop by having patrols in the fishing area and banning the use of illegal fishing tools (number 6 in Fig. 5). They want increased protection of the forests (be it from foreign companies, illegal logging, or other pressures) in order to stabilize rainfall patterns, and believe that wildlife will return if the environment is better taken care of. They also believe that the reduced water quality can be improved by assigning a specific area for grazing, and farmers stress that pastoralists should reduce the number of cattle (number 2 in Fig. 5). This view is not shared by the pastoralists, who acknowledge the impacts on water but do not want to change their herding practices.

Fig. 5. Future aspirations of the participants in Mkangawalo Village. The youth want the company to stay, but only if they have increased participation and authority over company decisions (1) and better working conditions (3). They want the pastoralists to reduce the number of cattle and to graze the animals in a specific area in order to improve water quality of the rivers (2) and they want illegal fishing to stop by having patrols in the river (6). They suggest fishponds, beekeeping, and a small-scale oil palm factory as alternative incomes (4, 5).

Fig. 6. Future aspirations of participants in Nakafulu Village. Here, also, the youth want the company to stay, but only if they have increased participation and authority over company decisions (1). They want the company to increase the buffer zone along the rivers and replant natural vegetation to improve water quantity and quality (2, 3). They suggest that the company should give back the land they are not using in order for farmers to grow rice (4).

Participants also have several suggestions for alternative incomes, such as fishponds, beekeeping, and a small-scale oil palm factory (numbers 4 and 5 in Fig. 5). In the village that leases land to KVTC, many people want the company to give back the valley land that they are not using for teak production so that farmers can expand their rice fields (number 4 in Fig. 6). Important to note is that, in both sites, the youth who were part of the painting process wanted the companies to stay, but only if they offer fair and secure employment for local residents (number 3 in Fig. 5). Older people could generally not see any benefits from the presence of the companies in their current form and were concerned for younger generations, but felt powerless due to government support of the companies. If they had the power, they would want the companies to leave or only act as a buyer while leaving production to the local farmers. Contrasting future aspirations like presence of the company, irrigation, and grazing of cattle were dealt with in different ways—by focusing on the aspirations of the youth (presence of the company), the main aspiration (irrigation), or the only suggested alternative to a current challenge (grazing and number of cattle).

DISCUSSION

Reflections on the findings

Visualizing the past, present, and future through participatory art, in combination with conventional methods such as focus-group discussions, interviews, and observations helped us understand changing land use (e.g., its directionality, drivers, and impacts) from a landscape and livelihood perspective. In both case-study areas, land acquisitions represent one of the main drivers of changing socioenvironmental conditions, with direct and indirect effects that constantly influence each other and reshape the current state. Furthermore, participants rarely pointed out the companies as the only cause of environmental change, but also highlighted the consequences of population increase and expansion of conservation areas, which have an added effect on land available for livelihoods. It is, therefore, important to approach this phenomenon not in isolation, but as an additional pressure on communities that already have to cope with a variety of stressors. We found that local community members are often well aware of (and openly point out) multiple stressors, including those in which they themselves play a role.

An example of direct effect of changed land use from natural forests to teak is the perceived effects on yields of staple crops. Multiple causes were pointed out, including a change in pollinating insects and concerns that teak trees might absorb nutrients and water from the soils. An example of indirect effects is the increased pressure on forest resources and its connection to rainfall and water quantity in the rivers. In the case of KPL, the company itself is not engaging in deforestation, but their presence has forced local communities to encroach on the forest reserve for fetching firewood and timber. In combination with population growth, this has caused rapid illegal deforestation during the last decade, which might have shifted local rainfall patterns and decreased the volume of water in the rivers. On top of this, it is believed that the company further reduces river flows through irrigation. Our claim here is that the companies are not always directly responsible for environmental degradation in the valley, but that they must also be understood as an indirect force of societal and environmental change.

The study also shows that even when the arrival of companies is identified as a cause of environmental degradation and harassment while offering few economic benefits, removal of the company is not necessarily seen as the desired solution, especially among youth. Communities may instead wish for greater consideration of environmental impacts, decent employment opportunities, and influence on decision making. Many participants wish for a renegotiation of the 99-year lease as unforeseen population conditions have increased the pressure on land. Meeting the above conditions does not mean that large-scale land acquisitions of this type are fully accepted locally or should be considered as the only path to agricultural development—determining what interventions are best suited to sustainably fulfill national and local development aspirations is beyond the scope of this paper. What can be said, though, is that it is important to not make assumptions about what kinds of solutions those already impacted by land acquisitions wish to see. The alternatives to undesirable change do not need to equal reversal to past conditions.

Reflections on participatory knowledge production

The paintings are not meant to quantify land-system changes, but rather to visualize local perceptions of socioenvironmental change. Quantification of land-use and land-cover change are conventionally done by using methods like remote sensing and GIS, but these methods are incapable of capturing socioenvironmental change as experienced at the local level. By using participatory methods, we do not claim that the stories told by community members—or any other actors—should be taken at face value, but rather that lived experiences of socioenvironmental change are important both ethically and scientifically. This is particularly valuable when few data are available, making local knowledge indispensable for understanding both historical and current conditions. We recognize that local knowledge sometimes is insufficient in isolation (Riedlinger and Berkes 2001), and that people's memories and descriptions of past landscapes can be an unreliable source of accurate information about land-use change. Memories are selective and may be shaped less by actual observations of the physical environment than by interactions with past and current authorities, or individual experiences of economic hardship and scarcity (Boerma 2012). People might glorify the past, and some claims might be rumors and speculations. That said, even though participants' perceptions do not always coincide with "reality," it is their "subjective reality," that is shaping current and future behavior and land-system changes (Nightingale 2003, 2015). An example is a story about beacons that have been put up in the wetlands (middle left part of the painting of the present in Fig. 3). Several informants were very concerned that parts of the protected wetlands in the village have been leased to a foreign company. This was denied by an interviewee at the Ramsar office, who stated that the beacons mark where local farmers are not allowed to encroach. However, although it can be difficult for researchers to know if accounts are "correct," they can still be analytically valuable. The subjective reality described in this story says something about the (lack of) power and insight the local farmers have over land use and control, and their fear of further loss of land to investors.

Similar reservations can be held regarding participatory approaches for visioning the future; what is to say that "local"

visions are feasible, sustainable, or just? It is important to note that this type of visioning exercise does not aim to make predictions, or identify an ideal development pathway as in the case of explicit "sustainability visions" (Wiek and Iwaniec 2014). Rather, we see it as a way to start exploring alternatives and solutions to socioenvironmental problems from the viewpoint of groups that are underrepresented in the debates concerning development of their own societies.

Reflections on using participatory art as a method

As there are no blueprints for how to conduct this type of study, and not all turns of fieldwork can be foreseen, many methodological decisions had to be made or remade during the time in field. At first, it was difficult to balance the artist's focus on aesthetic quality, the researcher's focus on substance, and the participants' focus on painting a correct "map," but as the fieldwork progressed, the respective roles got clearer. After 3–4 d, the discussions started to get saturated in terms of substance, at which point, we moved on, rather than adding details for the sake of aesthetic perfection. It was very valuable to involve an artist familiar with the local techniques, where to get supplies, and who spoke the participants' language. There is a risk that visualization techniques reinforce cultural bias and power relationships if they are unfamiliar to participants (Campbell 2002), so using a well-known art style and collaborating with a local artist skilled in both painting and instructing was essential. It was also helpful to have an interpreter who was familiar with the subject matter, as she could help facilitate the discussions.

The most challenging part of the painting process was to depict future aspirations. As opposed to painting the past and present, where consensus could be reached through discussion, it was difficult to produce a common vision for the future because aspirations and interests differ among groups and individuals (e.g., the continued presence of the companies). The activity was still valuable for spurring discussions around future change, but as always, it is important not to seek homogeneity among "local people" (White 1996). Here, we see big potential for methodological development, to add opportunities for more in-depth discussions about pathways to a desirable future. This could involve different groups (livelihoods, age, gender) and selected stakeholders working with environmental issues, community development, and human rights in the area. Rather than producing one vision, different future scenarios could be explored as part of an action-oriented process (Oteros-Rozas et al. 2015).

Another methodological challenge was to select participants for the painting workshops. When the idea to paint was introduced at the focus-group discussions, few volunteered to participate, simply because they had never painted before. But when we explained that an artist would instruct them, more people agreed to participate. After making the first painting, it also became clear that three participants were too many, making the group inactive as a whole. By reducing the group to two participants, all were active through the whole painting process and discussions. Most participants in the painting workshops were farmers, which might have affected the representation of other livelihoods in the painting. Efforts were made by the researcher to remind the participants of what had been said during the previous focus group, and by having additional focus-group discussions with fishermen and pastoralists to make sure that their stories were represented in the paintings.

Limiting the participants to two might seem to have made the research process less inclusive. However, the painting workshops enabled us to open up the conversation more broadly to people who had not been included in the focus-group discussions. As we were painting outside the village office, many people stopped by and were curious to see what we were doing and were encouraged to add something to the painting in order to increase the inclusiveness and richness of the knowledge production. Passers-by also functioned as live peer reviewers by confirming, clarifying, or commenting on stories in the paintings. An example of this is passers-by discussing the past and the present, agreeing that they would prefer the present despite current challenges in terms of land availability, compared with the past when wild animals were the biggest threat to both lives and farming. Community members also tended to gather around the paintings, and participants explained the stories that were now visualized. This demonstrates the communicative qualities of using art for participatory knowledge production, as the paintings created a collaborative medium that enabled integrative communication (Clark et al. 2011, Zurba and Berkes 2013).

In addition to the communicative benefits of using art in the research process, the paintings themselves allow for communicating complexity in a way that generalized schematics or scientific texts cannot do in a condensed and readable way. This became particularly clear when we contrasted the generic schematic (Fig. 2) with the richness of the paintings, which simultaneously contain generalizable landscape-level trends such as forest-cover change and more context-specific processes observable only at the community or individual level. For example, increased participation of community members in company decisions could easily be represented in both paintings by people meeting under a mango tree, but would have been difficult to capture in a generalized schematic. The artwork has been used as boundary objects after the fieldwork in order to communicate local concerns to different stakeholders within and outside of academia through exhibitions at scientific conferences, open events, and at the National Museum and House of Culture in Dar Es Salaam, Tanzania.

CONCLUSION

In this study, we used participatory art in combination with conventional qualitative methods in order to coproduce knowledge about land-use change in villages affected by large-scale land acquisitions in Kilombero Valley, Tanzania, aiming to understand experiences, perceptions, and drivers of socioenvironmental change. The paintings illustrate how communities are facing increased pressure on natural resources due to multiple stressors: population growth, land acquired by transnational agribusinesses, and expanded conservation areas. In its interactions with already existing pressures, land acquisitions should be understood as both a direct and indirect force behind socioenvironmental change, rather than an isolated phenomenon. Future aspirations differ, and many among the youth want the agribusiness to stay—but only if community members can get increased authority over company decisions and can benefit from their presence.

We found that painting workshops functioned as a valuable method for cocreating knowledge about the past, present, and future in the context of land-use change because they enabled us to understand and communicate the complexities of

socioenvironmental change from a bottom-up perspective. Paintings functioned as boundary objects; a collaborative product that facilitated communication both between the researcher and affected communities and amongst community members. The art works have also been used as boundary objects after the fieldwork in order to communicate local concerns with regard to land acquisitions to different stakeholders within and outside of academia through exhibitions. Being a relatively novel approach, not least in this particular context, we encourage others to further explore the methodology to better understand its potentials and limitations.

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/8986

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Paper IV

Mixing methods to understand land system change in Kilombero Valley, Tanzania

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Keywords: Remote sensing; participatory research; mixed methods; large-scale land acquisitions; socio-environmental change; deforestation

ABSTRACT

Distant actors play an increasingly important role in raising the pressures on land and water resources, in turn affecting societies and ecosystems elsewhere. Large-scale land acquisitions are a critical contemporary driver of global socio-environmental change, in particular in the Global South. This study aims to understand the drivers and impacts of socio-environmental change in Kilombero Valley, Tanzania, which is a region that experience rapid land use and land cover changes due to the establishment of foreign and domestic large-scale farms, coupled with rapid population growth and expansion of small-scale farms. Remote sensing is a common tool to monitor environmental change, but often fails to explain the underlying socio-economic processes, which can be captured by qualitative participatory research methods. The aim of this research is therefore to analyse patterns and processes of socio-environmental change with these two research approaches. We use land cover categories established through local participation to classify Landsat satellite imagery and quantify land cover patterns of 2004 and 2014, in order to compare the environmental state before the arrival of the foreign agribusinesses with the current situation. The land cover change detection is thereafter combined with local perceptions of socio-environmental change from fieldwork, which gives us a broad qualitative and quantitative understanding of change in the area. The quantification indicates that the biggest land cover changes are seen in farmland (increased by 17.6%) and wetland (decreased by 16.3%), which is in line with local narratives. The land cover classification however shows a small increase in forest cover, which is not in line with the narratives of change that proclaim rapid deforestation. Our research shows that mixing remote sensing and participatory research can provide both complementing and contrasting perspectives of patterns and processes of socio-environmental change. This speaks for using interdisciplinary mixed-methods approaches for better understanding how distant drivers contribute to socio-environmental change elsewhere.

INTRODUCTION

Economic, political, and social change drive land use and land cover change (LULCC), which is a critical sustainability challenge due to its undesirable effects on the climate system, water resources, biodiversity, human welfare and development (Lambin &

Meyfroidt 2011; Turner et al. 2007). Land system science aims to understand the dynamics of LULCC as a coupled human-environment system (Turner et al. 2007; Turner & Robbins 2008; Verburg et al. 2015), focussing on the spatio-temporal patterns of change, as well as the underlying socio-environmental drivers, impacts, and feedbacks of land system change. A contemporary challenge within land system science is to understand the local effects of increased distal land connections due to the growing competition for land and water resources (Seto & Reenberg 2014).

Over the last two decades, there has been a rapid increase in large-scale land acquisitions for the production of fibre, biofuels, feed, and food for export, which has impacted ecosystems, agro-ecosystems, and societies, predominantly in the Global South (D'Odorico et al. 2017). Socio-environmental changes in the context of large-scale land acquisitions are highly complex and associated with several sustainability challenges, like deforestation (Davis et al. 2015; Feintrenie 2014), water scarcity and pollution (Dell'Angelo et al. 2018; Johansson et al. 2016), soil degradation (Lazarus 2014), food insecurity (Havnevik et al. 2011), and negative health impacts (Knoblauch et al. 2014). The use of natural resources by foreign actors often leads to conflicts over land and water between local and non-local land users (Hermele 2012; Schoneveld et al. 2010). Conflicting interests and agendas of local and non-local stakeholders make it difficult for researchers to navigate between the different actors, and it is often difficult to identify what socio-environmental changes actually take place. There is often a lack of social and environmental data in areas where land is acquired, which makes it difficult to compare results with a baseline representing the time before land was acquired.

Remote sensing-based land cover classification is a well-established method for quantifying patterns of land change across time and space (Brannstrom & Vadjunec 2014), and has a good record for informing decision-makers for improving natural resource management (DeFries 2008). The method can be used to investigate environmental change, without the interference, interests, or agendas of others (except the researcher him- or herself). However, without relating the observed changes to experiences on the ground, it fails to identify the underlying societal drivers and land-use practices that give rise to environmental change, and how the changes in turn affect people (Jiang 2003; Liverman et al. 1998; Nightingale 2003; Robbins 2003). There is therefore a growing recognition that interdisciplinary research and co-production of knowledge is needed to better understand drivers, impacts, and feedbacks of land system change, by linking experiences on the ground to pixels and patterns in satellite images (Brannstrom & Vadjunec 2014; Fox et al. 2003; Herrmann et al. 2014; Liverman et al. 1998; Turner et al. 2007).

Co-production of knowledge is essential for linking science with societal needs, which in turn is vital for facilitating sustainable development based on local challenges and concerns (Jerneck et al. 2011; Kates et al. 2001; Verburg et al. 2015). Accordingly, researchers need to provide social meaning to the image interpretation by integrating local experiences, and observations through ethnographic and participatory research methods (Chambers 1994), such as focus group discussions (Kitzinger 1994), narrative walks (Jerneck & Olsson 2013), semi-structured interviews (Kvale 2008), and field observations (Turner et al. 2007).

In this article, we apply a mixed-methods approach in order to co-produce knowledge about socio-environmental drivers and impacts of land-use and land cover change in the context of large-scale land acquisitions. This study builds on earlier work by Johansson and Isgren (2017) in that it combines participatory methods, based on local knowledge and experience, with remote sensing, based on exploratory tools for change detection and analysis. The novelty of this study is that the land cover classification is developed in consultation with local land users prior to the classification, and is therefore based on local concerns. In this way we are able to understand the local meaning and experience of change, while also exploring the spatial extent and remote visibility of change of land cover categories that are of importance for people vulnerable to socio-environmental change.

The main objective of this study is to develop a good understanding of how the environment is changing in the Kilombero Valley, Tanzania, which is an area subjected to large-scale land acquisitions for rice production. Mixed methods provide a more nuanced understanding than one method in isolation, which is why we aim to shed light on how, and if, environmental change perceived by local farmers, fishermen, and pastoralists can be observed in satellite imagery over the area. We ask the following research questions by comparing the two methods: 1) what are the dominant narratives of socio-environmental change identified with participatory research approaches? 2) What are the land use and land cover changes between 2004 and 2014 observed with remote sensing? 3) How do local perceptions of change in forest, shrubland, grazing land, farmland, wetland, and water, compare to identified land cover changes through land cover classification of the same categories?

CONTEXT

Large-scale land acquisitions: a dominant driver of socio-environmental change

Large-scale land acquisitions are rapidly transforming ecosystems and societies in many of the low-income countries of the world, especially in Sub-Saharan Africa (Anseeuw et al. 2012; Messerli et al. 2014; Seaquist et al. 2014). African agriculture is often depicted as stagnant, underproductive and in need of modernization and intensification (Van Ittersum et al. 2016). Responsible investments in agriculture have the potential to spur economic development, boost agricultural yields and contribute to food security (Deininger & Byerlee 2011). But critics describe the current trend of land acquisitions as a form of land grab due to unequal power dynamics, and an involuntary transfer of land rights from small-scale farmers to powerful foreign or domestic investors (Borras et al. 2011; Cotula 2013; Davis et al. 2014; Edelman et al. 2013; Havnevik et al. 2011; Hermele 2012).

One reason for the rapidly increasing number of land deals in Tanzania (and particularly Kilombero Valley) is the initiative "Southern Agricultural Growth Corridor of Tanzania" (SAGCOT), which was launched in 2011 in order to coordinate agribusiness partnership between the Government of Tanzania, private companies, and international donors to improve food security by reducing yield gaps and rural poverty, and also sustain the

environment (SAGCOT 2018). It is however questionable to what extent this has been achieved (Bergius et al. 2018; Locher & Sulle 2013), since most land has been acquired for water demanding and non-edible crops for fibre, and biofuel production (Johansson et al. 2016).

Current research suggests that land acquisitions are detrimental to local livelihoods and the environment (Bergius et al. 2018; D'Odorico et al. 2017; Dell'Angelo et al. 2018). Societal costs relate to the violation of local farmer's land rights, decreased food security (De Schutter 2011), and lost access and degradation of natural resources and ecosystem services that people depend on for their livelihoods (Deininger et al. 2011). Environmental impacts are not as well covered in the scientific literature, and reported effects relate to biodiversity loss from deforestation (Feintrenie 2014; Priess et al. 2007; Schoneveld et al. 2010), and reduced water availability and quality from intensified extraction and heavy use of chemicals (Johansson et al. 2016; Williams et al. 2012).

Land acquisition in Kilombero Valley

The study area is located in Kilombero Valley, a region experiencing rapid expansion of foreign and domestic investors, with companies transforming natural vegetation or small-scale farming areas to large-scale teak, sugarcane and rice plantations. In this study we focus on Kilombero Plantations Limited (KPL) that were entitled 5818 ha of land in 2007, in order to grow rice. The plantation is based on a public–private partnership between Agrica Tanzania Ltd (a subsidiary of the UK-based company Agrica Ltd), and the Tanzanian agency Rufiji Basin Development Authority (RUBADA). The company also receives a significant amount of funds from the Norwegian government, through their investments in Agrica Ltd via Norfund (Bergius et al. 2018).

The KPL farm covers large parts of three villages (grey areas in Figure 1) that have a long history of foreign investments, starting in 1986 with the North Korean-Tanzanian joint cooperation, KOTACO. KOTACO was the first company to change the natural landscape at a large scale by draining swamps, and clearing natural forests to establish 2000 ha of rice fields (Personal communication with KPL staff, March 2015). The farm was abandoned in 1995, and between 2000 and 2004 a US-Tanzanian company, Kilombero Holding Company (KiHoCo), re-established about 400 ha or rice fields but stopped their production soon thereafter. When KPL arrived in 2007, the company displaced 630 families that had re-settled and re-cultivated the area (Personal communication, March 2015).

Climate and ecosystems

Kilombero Valley is called the "Breadbasket of East Africa" due to its ideal conditions for agriculture with its fertile soils, and abundance water (Mombo et al. 2011; SAGCOT 2012). The area receives 2000-3100 mm of rainfall per year over two rainy seasons from March to May, and October to December. The uneven rainfall distribution contributes to considerable seasonal variations in water flow, creating a wide variety of wetland types.

Multiple rivers feed the floodplain, which covers approximately 8000 km^2, making it one of the largest freshwater wetlands in East Africa (Kangalawe 2005). The interactions between water, soils, topography, plants and animals make the Kilombero Valley a

biodiversity hotspot and a highly productive ecosystem (Mombo 2011). Some important functions of the wetland are groundwater recharge and discharge, flood control, nutrient cycling, and a water supply for agriculture, fisheries, and industrial use. Its ecological importance, and agricultural potential, have created strong global and local interest to both protect and exploit the land, which currently has game reserves, national parks (Selous, Udzungwa), conservation areas (Ramsar), as well as multiple large-scale agricultural plantations (Figure 1).

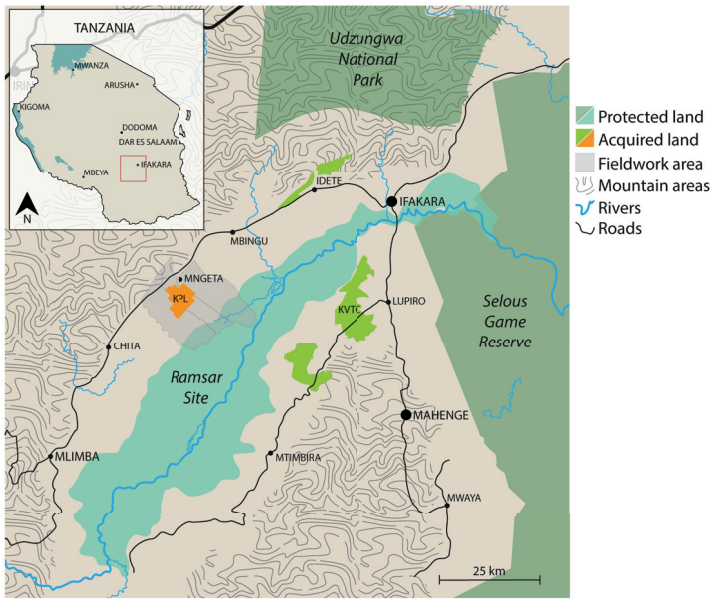

Figure 1. Map of Kilombero Valley, Tanzania, showing the distribution of protected land, acquired land, and the village land where fieldwork was conducted.

People and livelihoods

Most people in Kilombero Valley live in rural areas (76%) and largely engage in food crop production. Farming, fishing, and pastoralism are dominant livelihoods, which closely connect people to the environment, making them particularly vulnerable to environmental change (Kangalawe & Liwenga 2005). Maize is the main staple food of the region, and dominates agricultural production. But households also grow rice, cassava, banana and other crops. From 2002 to 2012, the rural population of Kilombero District increased by 24%, from 231,000 to 304,000 (NBS 2016). Part of the reason for this population growth, other than the high birth rate, is the recent immigration of pastoralist and agro-pastoralist groups like Masaai, Sukuma, and Barbaig, as well as business people, from all over the country (Nindi et al. 2014).

Despite the importance of the Kilombero Valley for food production in East Africa and for global conservation efforts, the area has received relatively little research regarding land change. This is partly due to the lack of data and paucity of cloud-free data for remote sensing analysis, which highlights the need for alternative research approaches to

understand socio-environmental drivers and effects of LULCC. We therefore combine the best available satellite imagery with participatory research approaches in order to complement local knowledge and bridge the gap between qualitative ethnographic and quantitative empirical approaches of knowledge production.

MATERIALS AND METHODS

Participatory methods

This study builds on knowledge and experiences gained from fieldwork in Kilombero Valley during March and April in both 2015 and 2016. The materials and methods for this study are described in detail in Johansson and Isgren (2017). This fieldwork relies on participatory methods to explore natural resource use and local perceptions of socio-environmental change in villages that lease land to foreign agribusinesses. The three villages that lease land to KPL have a population of about 23,000 (Population and Housing Census 2012), and cover about 570 km^2 (36% of the classified satellite images). The village land is marked in grey in Figure 1.

Focus group discussions were held in Swahili together with a translator, and included farmers, fishermen/farmers, and pastoralists/agro-pastoralists, with an equal representation of gender and age groups (approximately 12 people in each focus group). These participants were purposefully chosen since they represent the dominant livelihoods of the area, and directly depend on access to land and water resources. Questions were open-ended and focussed on natural resource use and change over the last decade, reasons for the change, and how different livelihood practices have been affected by the perceived environmental change. In total, five focus group discussions were held: three with mixed participants (one in each village), one with pastoralists/agro-pastoralists, and one with fishermen, since they were slightly under-represented in relation to farmers in the mixed group discussions. The focus group discussions formed the basis of a painting workshop, as they highlighted the main stories of, and concerns about, socio-environmental change.

Participants (two for each painting) were selected from the focus group to take part in a painting workshop where they explained and visualized the past and present socio-environmental state of their village and surrounding environment, in terms of natural resources and human activities. The narratives were based on what had been said during the focus group discussions, but details were added or modified by people who passed by and reviewed what was visualized. The focus on different time periods was a means to capture how people experience changes in their environment, including the relation between community and land use. A more detailed description of the participatory art method is provided in Johansson and Isgren (2017).

A second field visit was conducted in March 2016, where several visits to the wetland, farmland area, and mountain forest were made area in order to identify areas that have changed and not changed over the last decade. These locations have been used to support

land cover classification of satellite images over the fieldwork area, and are marked as red points in Figure 2.

Satellite observations

In this study, we add a remote sensing analysis to the local perceptions of socio-environmental change, and quantify the land cover changes described in field. We use two years, 2004 and 2014, for the analysis of the satellite data. Year 2004 was chosen because it represents the period three years before the arrival of the agri-business, and year 2014 was selected to represent the current state of the area. The use of two time slices enables the evaluation of changes in land before and after abrupt events, such as construction, deforestation, or natural disasters (Bae & Ryu 2015; Ishihara & Tadono 2017). The satellite data were standard Level-1TP with a resolution of 30x30 meters that had undergone terrain and precision correction to provide radiometric and geodetic accuracy. The Landsat data for 2004 was generated on July 17 by the Landsat 5 Thematic Mapper (TM), and the 2014 data was generated on July 13 by the Landsat 8 Operational Land Imager (OLI).

The remote sensing analysis was confined to a 40 x 40 km area (160 000 ha) (Figure 2), coinciding with the area of the participatory research, as well as some of the surrounding areas that were mentioned in fieldwork discussions in terms of nature conservation, and farmland expansion (i.e. wetland and mountain forest).

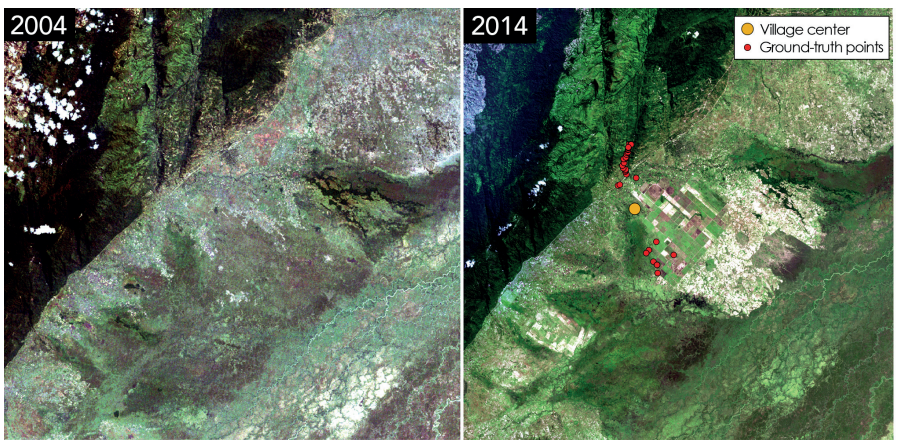

Figure 2. Natural colour composites of the study area from mid-July 2004 and mid-July 2014. The satellite image covers an area that is dominated by mountains and forests in the northwest, farmland and grassland at the foot of the mountains, and wetlands in southeast that are part of the Kilombero Valley floodplain. Red dots indicate transects for ground truth point collection.

Supervised land cover classification and validation

We performed a supervised classification of the study area for 2004 and 2014 (Figure 2), using satellite images from the dry season (mid-July) to minimize the influence of clouds. Supervised classification entailed field visits in order to identify sites that represent the

different land cover categories that should be classified (McCoy 2005). The classes were established from the discussions during fieldwork in 2015 (Johansson & Isgren 2017) where natural resources were discussed in general terms, e.g. forests, regardless of species type, and farmland regardless of small-scale or commercial agriculture. As a result, six land cover classes were identified: farmland, forest, grassland, shrubland, water, and wetland.

Training data are areas identified to represent the different land cover classes. Since the 36 geo-referenced points collected in field are not enough for serving as ground-truth points (red points in Figure 2), we used high-resolution imagery from Google Earth from August 2012 and July 2013 to collect training data for the 2014 land cover classification, based on local experience and knowledge. The supervised land cover classification was thereafter performed using a random forest classifier (Breiman 2001). This approach was chosen for three reasons: firstly, it is superior to parametric classification algorithms, such as Maximum Likelihood, that come bundled in remote sensing software (Hayes et al. 2014); secondly, it is straightforward to apply in open source software such as R and QGIS; and thirdly, it is in widespread use (Belgiu & Drăguţ 2016).

Classification was performed through the *randomForest* (Liaw & Wiener 2002) and c*aret* (Kuhn 2008) packages in R 3.3.0 (R Core Team 2016). The classification was thereafter validated with 60 random points per class as recommended in Congalton and Green (2008). For 2014, ground truth points were collected using a combination of field data and interpretation of high-resolution Google Earth imagery. No fieldwork was conducted in 2004 and no free high-resolution imagery for that year was available to the authors. Therefore, the Landsat image for that year was used for the selection of the reference data (Bagan et al. 2010; Vittek et al. 2014), using a combination of reflectance indices and false-color composites to distinguish between land cover categories.

Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Water Index (NDWI) were used to confidently characterize cropland and wetland areas, respectively, in the classification process. NDVI is the difference between near-infrared (850 – 880 nm) and red (640 – 670 nm) surface reflectance divided by their sum, and captures the spectral signature of live green vegetation (Rouse et al. 1973). NDWI is the difference between green (530 – 590 nm) and near infrared (850 – 880 nm) surface reflectance divided by their sum, and captures plant water content (Gao 1996). The overall accuracy of the land cover classification was computed by dividing the total number of correctly classified pixels by the total number of ground truth points. Thereafter, user's and producer's accuracy were calculated for each class, as well as confidence intervals at the 95% level as suggested by (Olofsson et al. 2014). The user's and producer's accuracy can show to what extent the map user and producer can trust the classification for each individual class (Supplementary Information). The change detection was done through mapping, and cross tabulation, to calculate the change of each land cover class between the two years of comparison.

Environmental data

Supplementary environmental data from two additional sources were included in the analysis in order to identify climatic variations in precipitation and vegetation greenness. This was done to see if there are other conditions besides anthropogenic changes that may explain differences between the two years of satellite observations. The first type of data was time series data on annual precipitation was obtained from Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS, Funk et al. (2015)), which is a quasi-global rainfall dataset, spanning 50°S-50°N (and all longitudes), starting in 1981 to near-present. CHIRPS incorporates 0.05° resolution satellite imagery with in-situ station data to create gridded rainfall time series for trend analysis. The second type of data on vegetation greenness was in the form of NDVI from the Moderate Resolution Imaging Spectroradiometer (MODIS). Time series of NDVI data around a 30 km by 30 km area centred on latitude -8.3874 and longitude 36.09167 were downloaded from the subsetting web service provided by the Oak Ridge National Laboratory (ORNL), and Distributed Active Archive Center (DAAC).

RESULTS AND DISCUSSION

According to the land cover classification, farmland is the category has changed the most (increased by 17.6%), mainly at the expense of wetland, and shrubland (Figure 3).

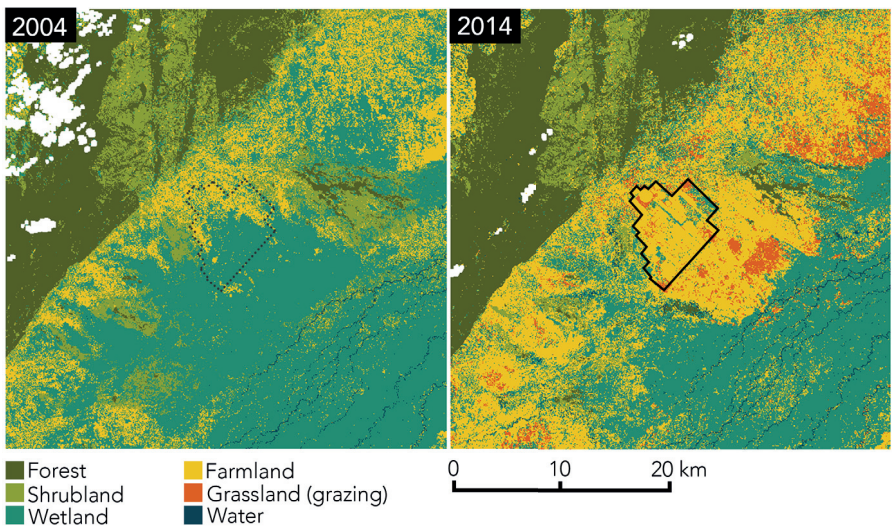

Figure 3. Land cover classification of Landsat images. The most visible land use change is the farmland expansion (yellow) to the wetland area (turquoise). Land acquired by KPL is delineated with the dashed black outline in 2004, and the solid black line in the 2014 image.

The results from the participatory research and those inferred from remote sensing land cover classification are presented for an initial overview in Table 1. Most results align except those regarding forest and water resources, where the participatory observations

point to deforestation and a decline in river water and wetland wetness, and the remote sensing shows a slight increase in both forest cover and areas with surface water.

Table 1. Comparing narratives of environmental change from participatory research and land cover classification using remote sensing. Arrows indicate negative or positive trends of a specific land cover type. A check-mark under "narrative alignment" means that the observed changes align, while a cross-mark means that observed changes diverge. A line means that it was not possible to properly observe any divergence or alignment of change with the chosen research approaches.

Land cover class	**Participatory art**		**Remote sensing**		*Narrative alignment*
	Pattern	*Driver*	*Pattern*	*Driver*	
Wetland	↓	Farmland and grazing land has expanded to the wetland area due to population growth and migration of pastoralist groups	↓	Farmland and grassland have replaced wetland	✔
Grassland	↑	Grasslands for grazing have increased due to increased cattle in the area, mainly in the wetland area.	↑	The land cover type was not classified in 2004 due to lack of ground truth data.	–
Farmland	↑	Farmland is increasing due to population growth and the establishment of a large-scale rice plantation.	↑	The farmland has increased at the expense of wetland and shrubland	✔
Forest	↓	Farmland expansion, charcoal production, and fuelwood collection are major drivers of deforestation.	↑	Shrubland (2%) and wetland (1.1%) have been replaced by forest.	✖
Shrubland	↓	Shrubs were removed when establishing the large-scale farm. This area was a major source for fuelwood.	↓	Shrubland has been replaced by farmland, wetland and forest.	✔
Water	↓	Rivers are drying out, especially in the dry season. The wetland is drying.	↗	Some wetland in 2004 was classified as water in 2014 indicating that wetlands are more wet.	✖

The overall accuracy of the remote sensing classification was 83% for 2004 (Table 2) and 85% for 2014 (Table 3). The change detection from cross-tabulation shows that farmland, grassland, forests, and water have increased by 281 (17.6%), 79 (4.9%), 59 (3.6%), and 11 (0.7%) km2 respectively, mainly at the expense of wetlands and shrubland that decreased by 260 (16.3%), and 125 km2 (7.8%) respectively (Table 4 and Figure 4). Confidence intervals for each land cover class and year are shown in Figure S1. The user's accuracy for wetland in the 2004 image was the lowest (60%) compared to other land cover classes, which means that only 60% of the pixels in the classified image actually represent wetland on the ground. Similarly, in the 2014 image, farmland had the lowest user's accuracy (60%) relative to other land cover classes. This is

mainly due to difficulties to distinguish between wetlands and rice plantations based on spectral information.

Table 2. Accuracy assessment of the 2004 classification (60 validation points for each class, except farmland which has 59). The overall accuracy of the classification is 83%, with the highest user's accuracy in water and forest (100 and 92%), and the lowest user's accuracy in wetland (60%).

	Forest	**Wetland**	**Shrubland**	**Water**	**Farmland**	*Classification Pixels*	*User's Accuracy*
Forest	**58**	0	5	0	0	63	92%
Wetland	0	**50**	0	3	31	84	60%
Shrubland	2	5	**55**	0	1	63	87%
Water	0	0	0	**57**	0	57	100%
Farmland	0	5	0	0	**27**	32	84%
Ground Truth Points	60	60	60	60	59	**247**	
Producer's Accuracy	97%	83%	92%	95%	46%	*Overall accuracy*	**83%**

Table 3. Accuracy assessment of the 2014 classification (60 validation points for each class). The overall accuracy of the classification is 85%, with the highest user's accuracy in water, shrubland and grassland (100, 96 and 95%), and the lowest user's accuracy in farmland (60%).

	Forest	**Wetland**	**Shrubland**	**Grassland**	**Water**	**Farmland**	*Classification Pixels*	*User's Accuracy*
Forest	**59**	2	6	0	0	0	67	88%
Wetland	0	**46**	0	2	0	6	54	85%
Shrubland	1	0	**53**	0	0	1	55	96%
Grassland	0	1	0	**37**	0	1	39	95%
Water	0	0	0	0	**59**	0	59	100%
Farmland	0	11	1	21	1	**52**	86	60%
Ground Truth Points	60	60	60	60	60	60	**306**	
Producer's Accuracy	98%	77%	88%	62%	98%	87%	*Overall accuracy*	**85%**

Table 4. Cross-tabulation of land cover classes in 2004 and 2014 showing the total percentage of each land cover class for year 2004 (total 2004) and 2014 (total 2014). The diagonal shows the percentage of pixels classified the same in 2004 and 2014. Other cells show pixels that have been classified differently between the two years. For example, in 2004 48.3% of the pixels were classified as wetland, 25% of these are still wetland in 2014, while 18.3% has been classified as farmland, and 2.6% as grassland etc.

Land Cover 2004 vs. 2014	Forest	Wetland	Shrubland	Grassland	Water	Farmland	Clouds	**Total 2014**
Forest	**16.0%**	1.1%	2.0%	0.0%	0.0%	0.2%	2.3%	**21.4%**
Wetland	0.4%	**25.0%**	3.1%	0.0%	0.0%	3.4%	0.2%	**32.0%**
Shrubland	0.8%	0.7%	**4.4%**	0.0%	0.0%	0.4%	0.2%	**6.5%**
Grassland	0.0%	2.6%	0.3%	**0.0%**	0.0%	2.1%	0.0%	**4.9%**
Water	0.0%	0.6%	0.1%	0.0%	**0.4%**	0.1%	0.0%	**1.2%**
Farmland	0.3%	18.3%	4.5%	0.0%	0.0%	**10.0%**	0.5%	**33.7%**
Clouds	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	**0.0%**	**0.3%**
Total 2004	**17.8%**	**48.3%**	**14.3%**	**0.0%**	**0.5%**	**16.1%**	**3.1%**	

The participatory research highlights that local communities experience increased pressures on land and water resources over the last decade. People explain that the increased pressures on land and water resources have altered the availability and accessibility of natural resources for local communities, creating new socio-economic challenges since few local residents have been able to find satisfactory alternatives to replace their traditional livelihoods of farming, fishing and pastoralism. Participants trace these challenges to multiple pressures, including rapid population growth, in-migration of people and cattle, nature conservation, and re-establishment of large-scale agriculture. In Johansson and Isgren (2017) social and environmental changes are depicted as painted narratives, and shows deforestation, wetland degradation, decreased water quantity and quality in rivers, and reduced fish and wildlife (Figure S2).

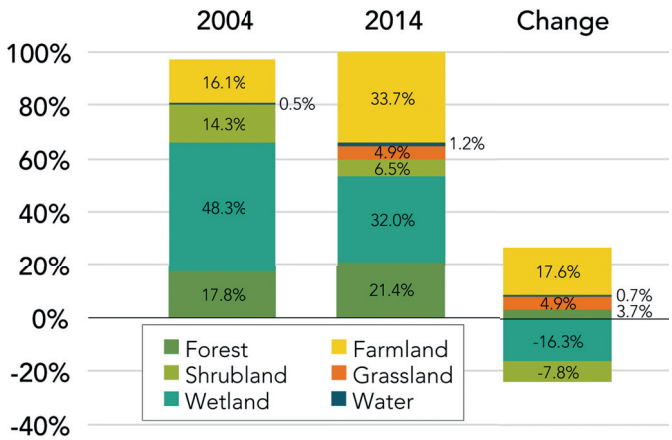

Figure 4. Changes in land cover, comparing the classification of 2014 with 2004 in total area and fractional change. The biggest changes are increases in farmland and decline of wetland and shrubland.

The farmland expansion to the wetland areas is visible at the foot of the mountain (yellow areas in Figure 3). According to the land cover classification, farmland is the category has changed the most (increased by 17.6%), mainly at the expense of wetland, and shrubland (Table 4). This indicates that farmland expansion is the dominant driver of decreased wetland and shrubland areas, which is in line with narratives of change from the participatory research. People explain that the largest driver of environmental change is farmland expansion into the wetland area, both due to the establishment of large-scale rice plantation by KPL, and population growth, which has caused a shift in small-scale farming areas and settlements towards the wetlands. Wetlands have also been reduced due to grassland expansion from rapid increase of pastoralists and cattle to the area during the last decade (2.6% of wetlands in 2004 are grassland in 2014, see Table 4). The farmland expansions and increased pastoral activities in the area have in turn caused conflicts between conservation authorities and local land users (Nindi et al. 2014).

Another significant environmental change mentioned during fieldwork is the reduction of forest cover. Participants describe three different forests in the area: one with large trees for timber that is located far away from the village, towards the wetland, which has

not changed much due to its distance from the village. Another forest patch that is closer to the village has decreased rapidly due to increased fuelwood collection, described as a consequence of the removal of shrubland areas for the large-scale rice plantation. A third area is the protected mountain forest area, which has been shrinking rapidly over the last decade due to illegal activities including farming, charcoal production, and collection of timber and fuelwood. These changes could not be confirmed by the remote sensing mapping, which indicate that there might be a mismatch between people's perceptions of space, and the exact extent of the Landsat mapping.

In contrast to the narratives of deforestation, the land cover classification showed that total forest cover had increased by 3.6%, from 284 to 343 km^2 (Table 4 and Figure 4). However, 2.3% of what was classified as forest in 2014 was covered with clouds in the 2004 image, and it is reasonable to assume that this was also forest in 2004, which makes the increase slightly smaller (1.7%). Two plausible explanations for this disparity are that either the deforested patches are smaller than the resolution of the Landsat imagery, or that deforestation occurs in understory clearings with rapid re-growth of grass and shrubs and thus not visible to the satellite. A narrative walk with a forest ranger in the mountains was conducted during fieldwork in 2016 in order to corroborate the local perceptions of deforestation. The vast deforestation of the mountains was not obvious when viewing the forest from the valley. However, when walking in the forest it was clear that there were numerous cleared plots for farming that were not visible from the outside. Similar counter-narratives were found by Fairhead and Leach (1995) who studied deforestation in West Africa and hypothesize that scientific assumptions about forest degradation did not correspond to the local narratives of complex socio-environmental interactions on the ground.

Forest degradation for fuelwood and other non-timber forest products is notoriously difficult to observe using a coarse or medium resolution of satellite images, unless the exploitation is intense (DeFries 2008). Sources of misinterpretation are related to issues with spatial resolution, as well as definitions and classification of land cover types. First, the resolution of Landsat (30x30 meters) makes it difficult to capture the cleared fields that are about 0.4 hectares in size. If cleared patches are also quickly overgrown with vegetation it is difficult to observe the patchiness at such a low resolution. A second reason for diverging narratives of forest cover is that the researcher and local participants define and classify forests and shrubland differently due to a difference in land cover class perceptions (Comber & Kuhn 2018; Robbins 2003). According to the land cover classification, shrubland declined by 7.8%, and during fieldwork interviews and focus group discussions the participants did not make a clear distinction between shrubland and forests, but rather referred to the resources they obtained from those ecosystems (e.g. fuelwood, timber, charcoal). For example, one of the farmers said *"In the past I could access forest in the planted area (KPL), now I have to walk further to collect fuelwood"*. Another interviewee described how the largest trees were cut down in 1989 by the first international agribusiness in the area, and that people in the village rarely had to cut trees in the past to fetch fuelwood since there was plenty of fuelwood from just picking up fallen sticks or cutting branches. The interviewee continued by saying *"KPL cut down all remaining forests in the plantation area, when people came to take fuelwood from the already*

cut down trees they were beaten. Then KPL burnt it all". Nightingale (2003) experienced a similar disagreement in her research about a community forest in Nepal. People perceived an improvement of the forest cover, while no large changes were seen in the aerial photo interpretation. One of the reasons for this was because the participants defined shrubs as forests, while the researcher separated these two classes.

Finally, participants expressed concerns about changing dynamics of water resources, such as a decline in river water. They trace this to irrigation, and further believe that deforestation affects rainfall and contributes to lower water levels in the rivers. Fisherfolk describe lower fish stocks in the rivers due to lower water levels, but also from overfishing since people lost access to land where they used to farm (causing a shift to fishing), and draining of swamps where they used to fish. According to the land cover classification, surface water areas have increased slightly by 11 km^2 (0.7%) (Table 4 and Figure 4). The supplementary environmental data over the study period revealed no large differences in precipitation (Figure S3), or negative trends in NDVI from year 2004 to 2014 (Figure S4). Detailed data on river flow, and irrigation extractions would be needed to accurately assess changes in water dynamics in the area, but the lack of historical data makes it impossible to compare current water extractions with a baseline. It is however reasonable to assume that river water has declined as an effect of the sprinkler irrigation systems implemented by KPL.

Strengths and limitations of the two research approaches

Wetland and farmland were the two land cover categories that were most difficult to classify, even though the farmland expansion was unquestionably visible in the satellite imagery. This underscores that interpretation based on texture (like object-oriented classification), and not only spectral differences, could be used to improve the distinction between farmland and wetland (Elmqvist et al. 2008). The low user's accuracy (60%) for farmland in 2014 and wetland in 2004 means that there is likely an over- and underrepresentation of those classes in those years (Table 2 and Table 3). It is notoriously difficult to distinguish between wetlands and smallholder farmland during the dry season when there are patches of fallow land (Montandon & Small 2008). Wetland areas did not exhibit a distinct spectral signature in the study area due to the extensive presence of smallholder rice plantations, which might have resulted in spectral mixing of these land cover types. Mwita (2013) reported a similar problem in classifying land cover in Tanzania where wetlands could not be separated from field crops such as maize due to mixed cropping with wetland vegetation like typha.

The contrasting results regarding change in forest are a good example of how all knowledge is partial, contextual, and linked to how it is created (Nightingale 2003; Nightingale 2016). People who actively engage with the land have a sensitivity to register critical and unusual signs and signals in the environment, and can indicate which land cover classes are important, where they are located, and how they change (Berkes 2010). Without merging results from the two methods it would not have been clear that there is a disagreement in current changes of forest cover. It is in the disagreement that we can identify uncertainties in different methods, and where it is important to integrate

qualitative and quantitative approaches for a better description of socio-environmental change. In this case, remote sensing was not sufficient for describing the locally experienced changes in forest cover. The mismatch between experienced change and identified change raises a warning flag for decision-making based on solely quantitative estimates of land cover change, and problem formulation based on one method in isolation.

Local knowledge might be insufficient as an end in and of itself, and can be skewed by selective memories that are shaped less by observations of the physical environment than by individual experiences of economic struggles and scarcity (Boerma 2012; Riedlinger & Berkes 2009; Weber 2010). People might envision a better past, or have different visual interpretation of land cover types (Tveit et al. 2006), and as such they cannot provide spatially explicit quantitative information on change. People's experiences are however linked to how they use natural resources, and can point to current challenges of changing ecosystem services from these sources. Remote sensing is also subjective in the sense that the researcher often decides the number and type of land use classes, which affect what kind of land cover changes can be identified. What can be observed also depends on the spatial and temporal resolution, and interpretation of the satellite image. Land cover classification is therefore not free from biases, as the conversion of a satellite image into a land cover map involves binning of pixels into land cover classes by the researcher.

CONCLUSION

This study investigates what can be known about environmental change in an area that experience large-scale land acquisitions in Kilombero Valley, Tanzania. We used remote sensing, and participatory research methods for studying drivers and impacts of land system change in order to understand how distant actors affect land cover change. The land change detection could confirm local perceptions of farmland expansion to the wetland area, estimating that farmland (both large-scale and small-scale agriculture) increased by 17.6% between 2004 and 2014, while wetlands decreased by 16.3% over the same time period. No evidence was found to support local perceptions of rapid deforestation in the mountain area, as the land change detection estimated a slight increase (3.6%) in forest cover between the years of observation. Shrublands however declined by 7.8%, which points to either a misclassification, or different definitions, of forests and shrubland. Another reason for the lack of quantitative evidence for deforestation is due to under-story clearings, which are difficult to observe in satellite images, especially with the course resolution offered by Landsat. Only minor changes could be observed for grassland and water.

We conclude that remote sensing and participatory research approaches are two complementary methods for better understanding socio-environmental change, in particular in areas where there is a lack of historical data (e.g. maps, photos, satellite images with high temporal and spatial resolution, and other environmental data), which makes it difficult to compare the current state with a baseline of the past. The land cover classification provides a visual representation of the extent and patterns of different land cover types and how they have changed between 2004 and 2014. Remote sensing is

therefore relatively strong in its ability to quantify and map patterns of change, but provides limited descriptions of the underlying social, economic, or political drivers of change. Participatory methods however add more detail regarding the underlying socio-economic drivers, but fail to quantify and map large-scale patterns of change, which in turn is important for understanding the scale and locations of environmental change.

The results that were obtained by mixing top-down, and bottom-up research approaches made it possible to see where experienced change align or diverge with measured change. It is in the divergence that it is possible to identify new research gaps, as well as strengths, and weaknesses of the chosen research approaches. Political, historical, and economic interests and agendas affect knowledge production, which makes it difficult to find the truth, particularly in areas where there are unequal power-relations between different natural resource users. In this case, we removed some of these subjectivities by mixing participatory approaches with remote sensing, and developing land cover categories based on local knowledge and concerns. Furthermore, we highlight the importance to integrate lived experiences of change into natural resource management, and not base land use decisions on quantitative estimates in isolation. The combination of research approaches is useful for identifying limitations and divergence, thus opening up new research areas in need for further investigation and cross-validation.

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