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Review

Integrating evidence of land use and land cover change for land management policy formulation along the Kenya-Tanzania borderlands

Colin J. Courtney Mustaphi[a,b,*], Claudia Capitani[b], Oliver Boles[c], Rebecca Kariuki[b,d], Rebecca Newman[b], Linus Munishi[d], Rob Marchant[b], Paul Lane[e,f,g]

[a] Geoecology, Department of Environmental Sciences, University of Basel, 4056, Basel, Switzerland
[b] York Institute for Tropical Ecosystems, Department of Environment and Geography, University of York, Heslington, York, North Yorkshire, YO10 5NG, United Kingdom
[c] Department of Anthropology, University of Pennsylvania, Philadelphia, PA 19104, USA
[d] School of Life Sciences and Bio-Engineering, Nelson Mandela - African Institution of Science and Technology, P.O. Box 447, Arusha, Tanzania
[e] Department of Archaeology, University of Cambridge, Downing Street, Cambridge, CB2 3DZ, United Kingdom
[f] Department of Archaeology and Ancient History, Uppsala University, P.O. Box 256, 75105 Uppsala, Sweden
[g] School of Geography, Archaeology and Environmental Science, University of the Witwatersrand, Braamfontein, 2000, Johannesburg, South Africa

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ABSTRACT

This paper presents an overview of the scientific evidence providing insights into long term ecosystem and social dynamics across the northern Tanzania and southern Kenya borderlands. The data sources covered a range from palaeoenvironmental records and archaeological information to remote sensing and social science studies that examined human-environmental interactions and land use land cover changes (LULCC) in the region. This knowledge map of published LULCC research contributes to current debates about the drivers and dynamics of LULCC. The review aims to facilitate both multidisciplinary LULCC research and evidence-based policy analyses to improve familiarity and engagement between LULCC knowledge producers and end-users and to motivate research integration for land management policy formulation. Improving familiarity among researchers and non-academic stakeholders through the collation and synthesis of the scientific literature is among the challenges hindering policy formulation and land management decision-making by various stakeholders along the Kenya-Tanzania borderlands. Knowledge syntheses are necessary; yet, do not fully bridge the gap between knowledge and policy action. Cooperation across the science-policy interface is fundamental for the co-production of research questions by academics, policy makers and diverse stakeholders aimed at supporting land management decision making. For improved co-development and co-benefitting outcomes, the LULCC scientific community needs to mobilise knowledge for a broader audience and to advance co-development of relevant and meaningful LULCC products.

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* Corresponding author at: Geoecology, Department of Environmental Sciences, University of Basel, 4056, Basel, Switzerland.
E-mail address: colin.courtney-mustaphi@unibas.ch (C.J. Courtney Mustaphi).

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1. Introduction

The highlands and lowland semi-arid savannahs and woodlands along the Tanzania-Kenya borderland region are complex socio-ecological systems that are particularly sensitive to changes in climatic variability and land use (Rass, 2006; Mongi et al., 2010; ICSU, 2015), although the underlying human-environmental mechanisms of these processes are not fully understood (Grove, 1977; Willis et al., 2018). These ecosystems support a high biomass of domestic and wild mammals with human populations relying on these ecosystems for their livelihoods. Environmental and land use change vulnerabilities underpin the formulation of several of the United Nations' (2015) Sustainable Development Goals (SDGs) and other development goals. Climate changes, ecosystem degradation, biodiversity losses and sociopolitical pressures all impact development, conservation and livelihoods of socio-ecological systems along the Tanzania-Kenya border (Western, 2000; Sinclair et al., 2008a,b; Cai et al., 2013; IPCC, 2014). Agriculture, livestock and wildlife are impacted through the disruption of historically more reliable rainy and drier seasons (Munishi et al., 2015) modifying livelihoods and land management strategies (Reid, 2012; Goldman and Riosmena, 2013; Thornton and Herrero, 2015). Intensive land use of integration zones surrounding protected areas (Estes et al., 2012; Pfeifer et al., 2012; Veldhuis et al., 2019a) also places pressure on ecosystems and local populations that challenges the adaptive potential of rural communities (Gilbert, 2016). Generating scientific evidence on historical socio-ecological systems establishes a knowledge pillar that *can* inform present and future land management decision making.

Land use and land cover change (LULCC) research investigates the spatio-temporal characteristics and multiscalar processes of variability in Earth surface systems, including anthropogenic modifications (Foley et al., 2005; Ellis, 2007). But, signals of LULCC are confounding and challenging to disentangle (Loveland and DeFries, 2004), especially in retrospection. Understanding the character, timing and phase-relationships of these interactions is vital to the development of adaptive management plans, particularly with respect to savannah and forest ecosystems (Kruger, 2015). Accessible, transparent and reliable data repositories are necessary to apply knowledge and data in support of management planning (Wilkinson et al., 2016; Gorddard et al., 2016; Fig. 1). Knowledge is not the only pillar to function as a context for decision making. The pillars of societal rules and values are equally important and all interact and co-evolve as decision contexts. Concerted efforts in consensus-driven science that account for each of these interacting pillars and their inherent uncertainties should be at the fore of research used at the science-policy interface and developed for broad stakeholder audiences (IPCC, 2013; Cook et al., 2016). Knowledge products and services provide an evidence base for engaging stakeholders with tools for exploring, formulating, monitoring and adapting land management decisions (Magliocca et al., 2018).

In acknowledgement of knowledge and practice gaps, we present a LULCC knowledge mapping approach and its ongoing application to research at the borderlands of southern Kenya and northern Tanzania. This approach is especially important because, communication and mobilisation of synthesised scientific knowledge should be integrated within a model of continuous engagement between communities, local practitioners, policy makers, researchers and other stakeholders (Okello, 2005; Shetler, 2007; Reid, 2012; Reid et al., 2016; Løvschal et al., 2017; Galvin et al., 2018), in a manner that promotes community based decision making (Goldman and Milliary, 2014). As a contribution to addressing existing gaps, we review several disciplines active in LULCC-relevant research along the borderlands to identify the benefits and challenges of harnessing a broad evidence base to construct the knowledge pillar as a consideration in stakeholder dialogues and decision support. We develop this knowledge map and discuss future steps in anticipation of growing requests from non-academic stakeholders across the science-policy interface that scholars provide critical syntheses to support LULCC policy formulation. Communicating knowledge mapping is a useful precondition for integrated LULCC research and co-development of a research culture for engaging stakeholders interested in LULCC policy. Through an evidence-source classification and typology we interlink the dispersed state of LULCC knowledge products with the objective of improving multi-audience familiarity across the science-policy interface (Fig. 2). Developing new research insights of historical human-environment interactions that inform our future foresight tools also requires improved criticality on how best to mobilise this knowledge and integrate research cultures (Stump, 2010; de Bont et al., 2019) for application in policy formulation and decision support for land management within the borderlands (Fig. 2).

1.1. The scope of the review

The geographical scope of our review covers a complex region having a wide range of environmental conditions with steep gradients and high rates of change (Marchant et al., 2018), overlain with diverse socio-cultural histories and interacting spatiotemporal scales and trajectories of social interaction, exchange, cooperation and conflict (Reid, 2012). The temporal scope focuses from the mid Holocene onward that was characterised by high hydroclimatic variability after the African Humid Period, introduction of pastoralism, emergence of iron using material cultures, intensifying local-to-global connectivity, montane deforestation, defaunation, introduced species, and physical and jurisdictional fragmentation of landscapes. The borderlands of southern Kenya and northern Tanzania (henceforth the borderlands) host a rich diversity of environmental capital ranging from Kilimanjaro's peak

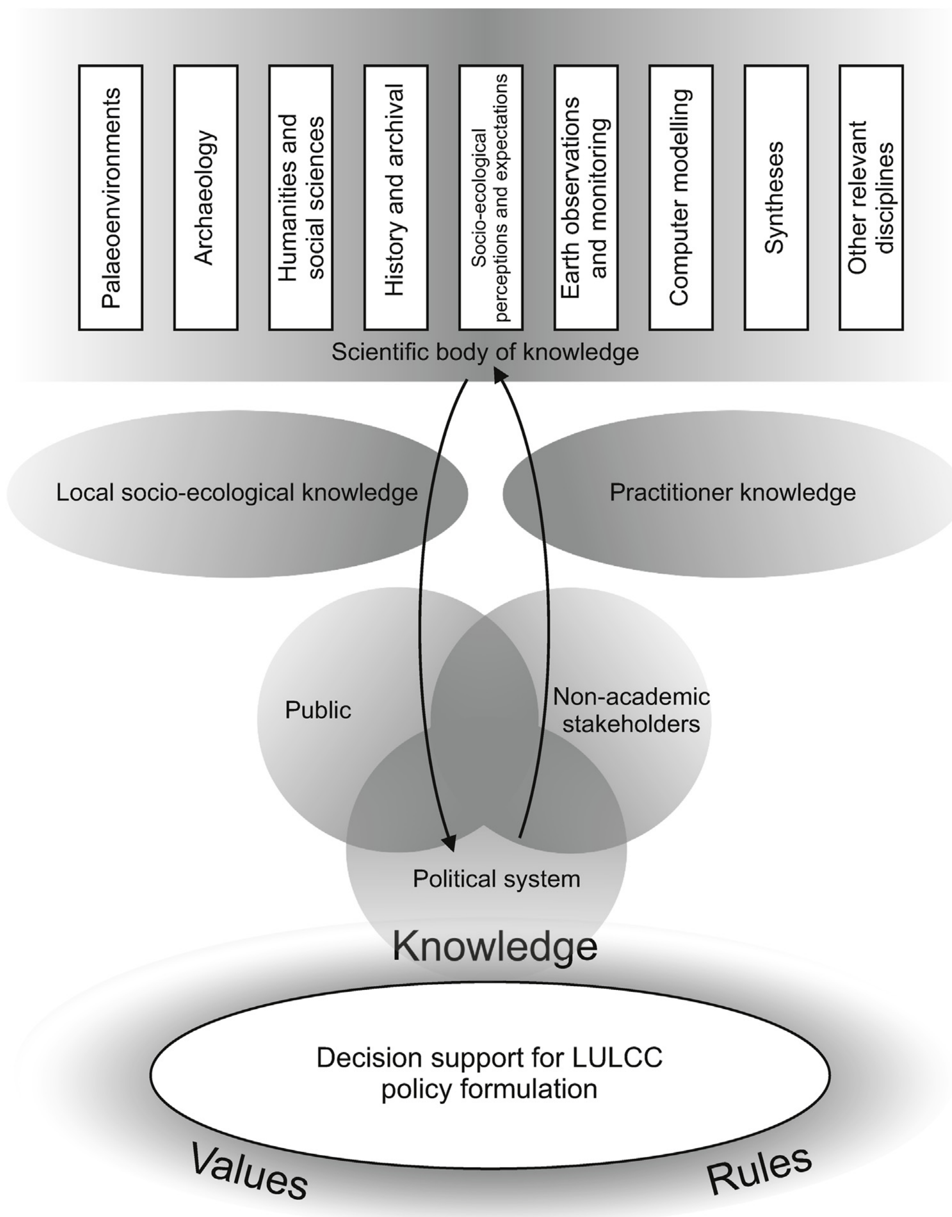

Fig. 1. Three pillars of decision context (at base: values, rules, knowledge; Gorddard et al., 2016). The knowledge pillar is explored and expanded to show the conceptual interactions across academic, political system, public, and non-academic stakeholder perspectives contributing, interacting and participating in knowledge production and end use. Note that knowledge is one pillar of context for decision making on LULCC policies, and equivalent explorations of societal rules and values are not explicitly explored in this paper.

with glaciers, montane forests and mesic woodlands, to semi-arid lowland savannahs and freshwater systems. The region is also rich in cultural diversity with a long and complex history of human-environment interactions (Marchant et al., 2018), but there are few transborder mechanisms for addressing ongoing LULCC challenges (Okumu, 2010). Currently, the borderlands include ethnically and culturally diverse urbanised and rural populations and multiple institutional actors and management regimes (Shetler, 2007; Sinclair, 2012). Past and present livelihoods range from shifting or intensive agriculture, livestock keeping, fishing, and hunting and gathering (Prendergast and Mutundu, 2009); alongside employment in tourism, conservation, resource extraction, and manufacturing, public sector, commercial and service industries (Homewood et al., 2009). The pressures on socio-ecological systems and anticipated consequences of future environmental and social changes are unevenly distributed - leaving ecosystems, communities and sections of society less adaptable and more vulnerable than others (Goldman and Riosmena, 2013; Kaye-Zwiebel and King, 2014; Miller et al., 2014; Salerno et al., 2016; Pecl et al., 2017).

2. Literature review

The knowledge mapping collated peer-reviewed publications and ongoing studies of LULCC at the borderlands since the mid Holocene (6000 yr BP) to present (CE2019) through a manual literature review of archaeological, palaeoenvironmental, remote sensing, historical, anthropological and ethnographic research (Fig. 3) using specific search terms (Supplementary Material, SM1). The search included digitally-available university theses and the few examples of grey literature produced by researchers known to have worked in the region. The review should not be considered

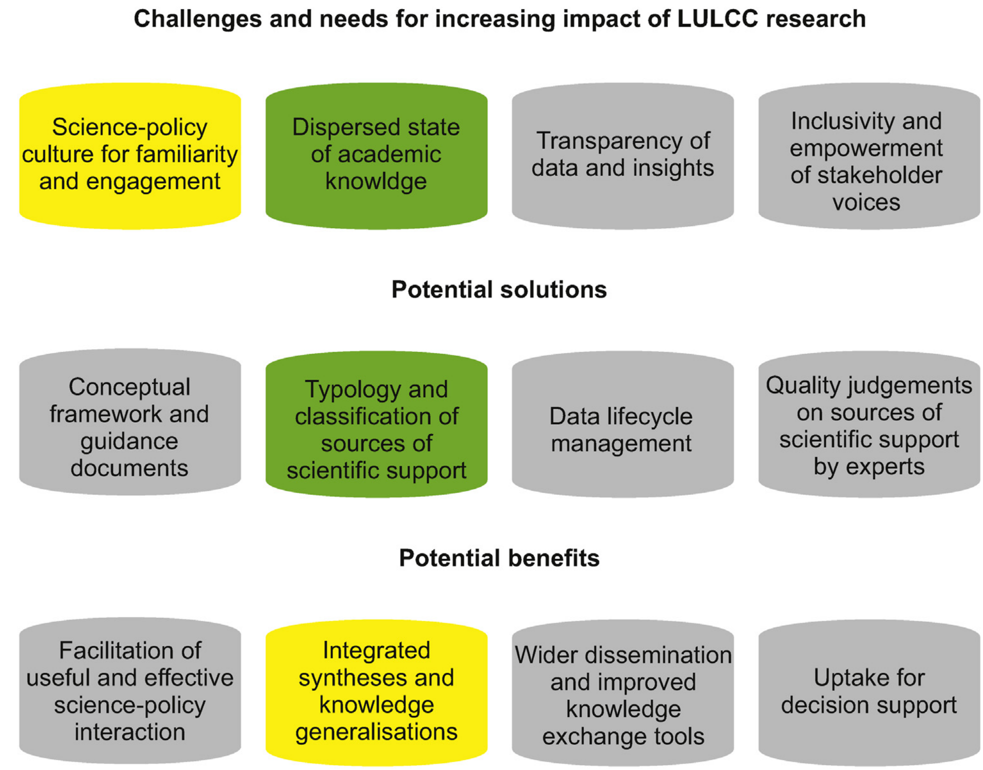

Fig. 2. A challenge, solutions, and benefits framework for science-policy engagement for LULCC research in support of land management policy formulation. We used these requirement perspectives to orient our research goals and in this paper we explore the dispersed state of knowledge sources (green boxes) in support of syntheses and improving familiarity across the science-policy interface (yellow boxes). Gray boxes represent other related aspects that are not the focus of this paper.

exhaustive. However, this review does not make use of the white papers, briefing notes, pamphlets and multimedia that capture non-academic viewpoints, writing for non-academic audiences and the policy landscape. We advocate that a review of these materials be undertaken as a future step. We have organised the evidence streams into categories based on the dominant approach used, while remaining aware of overlaps between disciplines as some studies are inherently interdisciplinary or used integrated research approaches (Fig. 4). In the next section, we characterise the research categories and discuss opportunities and caveats related to the evidence that each discipline provides on past, present and potential future LULCCs.

3. Typology of knowledge sources of land use land cover change (LULCC) research

3.1. Sources of terrestrial late Holocene palaeoenvironmental studies

Long-term archives of Earth system variability are primarily generated from geological evidence. Sediments, rock and biogenic

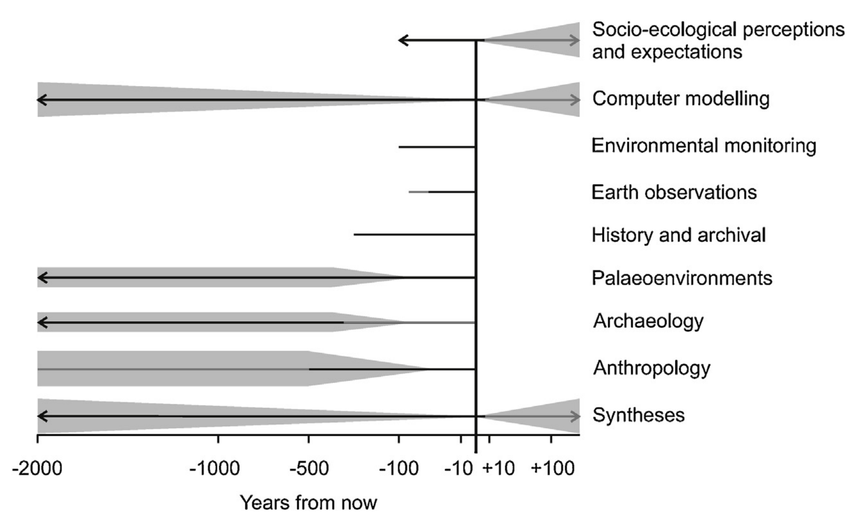

Fig. 3. Infographic of scientific evidence streams of LULCC and their temporal scope and potential ranges of relative uncertainties. Evidence streams of land use and land cover change and their associated temporal range coverage (black lines). Gray lines represent time intervals when coverage is less frequent due to the availability of records, sampling effort, or statistical properties of the available data. Gray envelopes represent the relative data and interpretation uncertainties that generally increase as you move away from the present day.

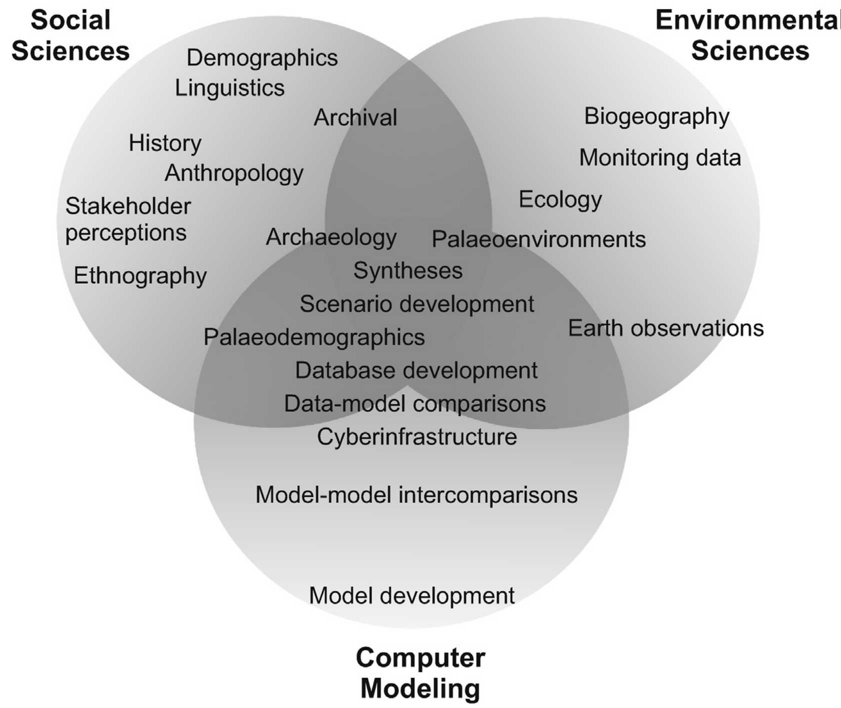

Fig. 4. Multidisciplinary linkages providing evidence streams of land use and land cover change.

deposits are analysed for physical, chemical and biological evidence of past environmental characteristics and variability (Last and Smol, 2001; Smol et al., 2001a, 2001b). Common geoarchives are lacustrine and palustrine sediments; cave deposits; and biogenic archives such as tree rings (dendrochronology). Robust geochronological data constrain the temporality of the information and archiving these data is crucial (Millard, 2014; Courtney Mustaphi and Marchant, 2016; Courtney Mustaphi et al., 2019). The spatial resolution of a geoarchive is often nested with frequently unquantified uncertainties and temporal resolutions are dictated by the characteristics and preservation of the material and the resolution of sampling and statistical analyses. Challenges and opportunities for applying palaeoenvironmental records to investigate LULCC in eastern Africa are numerous: these range of spatial and temporal biases, lack of taxonomic resolutions, and temporal uncertainties, through to not understanding the taphonomic issues associated with palaeoenvironmental data.

A total of 36 paleoenvironmental records have been published for the area (Fig. 5; Table SM2): with 13 sites in Kenya, 22 from Tanzania and one in Uganda (Lake Victoria). Lake sediment (n = 17) and peat (n = 10) core analysis were the most prevalent. Five studies included analyses of satellite or air photograph imagery. Other geoarchives used included four soil studies, three dendrochronological studies, one ice core record, and one fluvial sediment core analysis. The most frequent palaeoenvironmental proxy measurements were pollen (n = 23), charcoal (n = 13; see also Marlon et al., 2016), and sedimentology/geochemistry (n = 16). Other proxy measurements included diatoms (n = 7), sedimentary isotopes (n = 5), phytoliths (n = 4) and non-pollen palynomorphs (n = 3). Data sampling resolutions ranged from sub-centennial (n = 18) or multi-centennial (n = 14) and two studies provided sub-millennial data for the late Holocene. Two studies presented no geochronological data but likely date within the late Holocene. There were no studies with annual or consistent sub-decadal scale sampling during the late Holocene. Major challenges to mobilising these data are the variable data qualities, variety of metrics used and that only four sites have open access data availability (Table SM2).

Additional palaeoenvironmental records from nearby regions also provide regional insights to socio-ecological dynamics (Kendall, 1969; Talbot and Livingstone, 1989; Verschuren et al., 2002; Stager et al., 2003, 2005; Andama et al., 2012; Morgan and Lejju, 2012; Courtney Mustaphi et al., 2016; Nakintu and Lejju, 2016; Githumbi, 2017). Comparative analyses that bring together observations from modern ecosystems and paleoenvironmental records from the geologic record provide perspective and insights on contemporary discussions on environmental change and analogues for ancient human-environment interactions (Ashley et al., 2002, 2011; Deocampo et al., 2002; Lane, 2016). Research effort has focused around Lake Victoria and on highlands where permanent lakes exist with fewer explorations of deposits in semi-arid ecosystems. Large swathes across the borderlands have no palaeoenvironmental records; such as the Greater Serengeti Ecosystem, Kisii, Narok, Loita, western Kajiado, and the Rift Valley (Marchant et al., 2018) (Fig. 5). The semi-arid climate of the lowlands results in few locales where ideal geoarchive sampling targets have accumulated (Grove, 1977). Yet, in many key locations such as the Serengeti and Rift Valley, there are wetland deposits that accumulate palustrine sediments of the kind used successfully elsewhere in the region to reconstruct historical environmental conditions (Fig. 5: sites 5, 1, 14, 15, 25, 26: Gillson, 2006; Rucina et al., 2010; Githumbi et al., 2018a, 2018b; respectively) and there is great potential for soil-based palaeo-vegetation studies (e.g. site 13, Zech et al., 2011). This incomplete palaeoenvironmental history is compounded by the strong environmental, cultural, land use, and ecological gradients of the region that complicate meaningful spatiotemporal extrapolations. New palaeoenvironmental records from key socio-ecological systems focusing on relevant timescales and resolutions should be developed within multidisciplinary and multi-stakeholder projects.

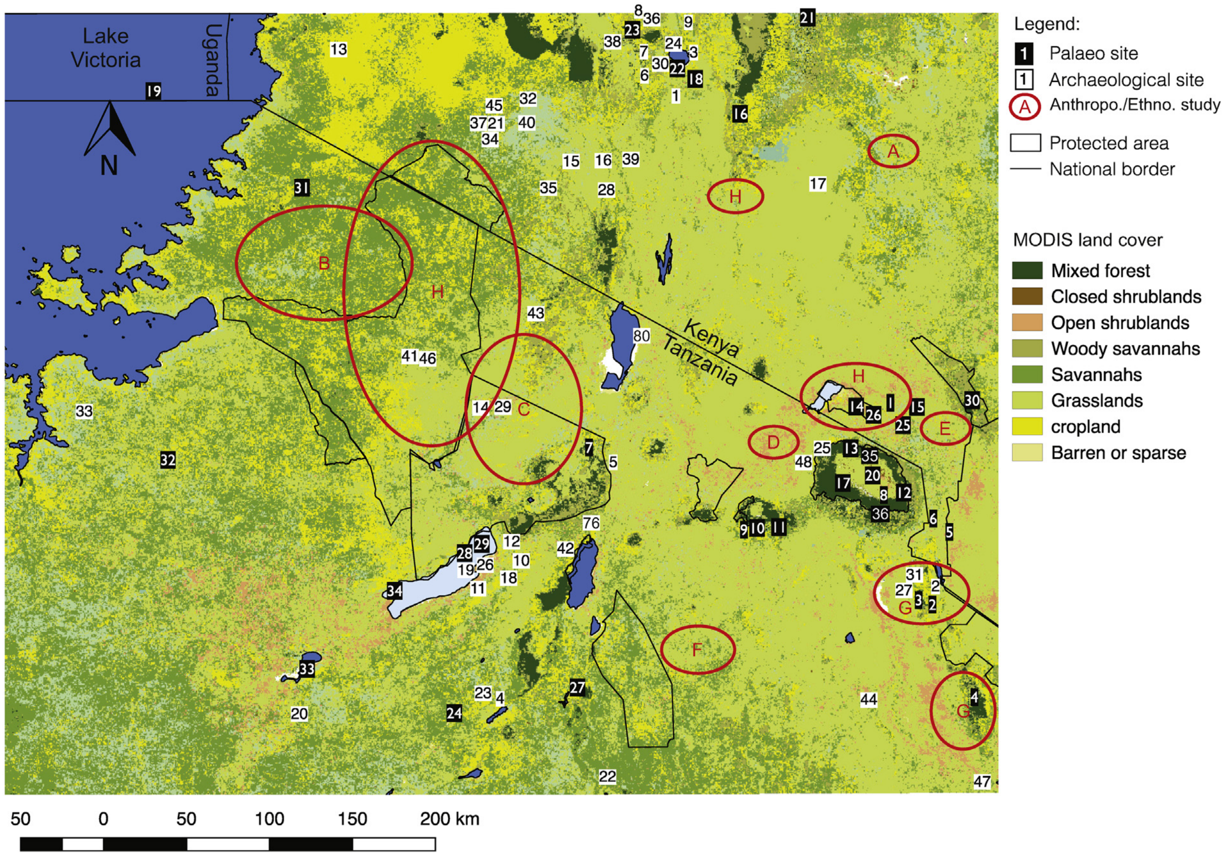

Fig. 5. Map presenting the palaeoenvironmental, archaeological and anthropological/ethnographic research in the Kenya-Tanzania borderlands. Numbers in black boxes are palaeoenvironmental sites presented in Supplemental Material (SM2) and numbers in white boxes show archaeological sites listed in Supplemental Material (SM3). Letters (red ellipses) present study regions of LULCC anthropological and/or historical research: A) Machakos, Kitui (Bernard et al., 1991); B) western Serengeti (Shetler, 2007); C) Ngorongoro and borderlands (Homewood et al., 2009); D) Engikareti (Butz, 2009); E) Chyulu Hills (Kamau and Medley, 2014); F) Simanjiro (Miller et al., 2014); G) North and South Pare Mountains (Håkansson and Widgren, 2007); H) Serengeti-Maasai Mara, Ngorongoro, Kaputiei, Amboseli (Reid, 2012).

3.2. Archaeological studies and survey areas

Archaeology provides evidence for human land and resource use, settlement, material culture, and connectivity that informs current LULCC narratives (Muchiru et al., 2009; Marchant and Lane, 2014; Lane, 2015a, 2015b). However, this is rarely a continuous temporal record and archaeological knowledge of LULCC is usually intermittent and synchronic. The archaeological literature demonstrates the complexity and fluidity of the spectrum of livelihood strategies in the borderlands, while offering insights into how hunter-gatherer-fisher, agriculturalist, and pastoralist livelihoods are expressed under varying environmental conditions and societal factors. There is strong evidence that people and cultures have had a high degree of fluidity between strategies and have shifted their identities accordingly (Kusimba and Kusimba, 2005; Crowther et al., 2017).

Archaeological surveying effort has tended toward areas where preservation is strong, visibility is high and access is possible. The intensity of archaeological exploration across the borderlands is variable and consequently future research may alter current understanding of the chronologies of significant land use changes, site distributions, and the processes and agents involved in initiating change (Marchant et al., 2018). In particular, spatial knowledge gaps occur at mid and high elevation mountain regions and across vast areas of savannah and bushland that have likely experienced extensive land use, limiting the potential to evaluate palaeodemographic assumptions prior to the European colonial experiences.

A total of 82 published archaeological sites are located within the borderlands (Fig. 5; Table SM3) and are unevenly distributed in space and time. More sites have certainly been documented in the relevant national sites and monuments registers, but are not considered here owing to the lack of detailed investigation and publication of these (e.g. URT, 1976; PPTCH, no date). Published sites dating to earlier intervals, c.6000-5000 BP, are much more frequent in Kenya than in Tanzania. Indeed, Kenya accounts for 48% of sites but comprises 32% of our geographic scope. The Rift Valley hosts the greatest concentration of sites, particularly toward Lake Naivasha (Fig. 5), and several records are found near Lakes Eyasi and Manyara (Mabulla, 2007; Prendergast et al., 2013, 2014; Seitsonen, 2006; Seitsonen et al., 2012), as well as Eastern Arc Mountains and the highlands around Narok and Lemek in southwestern Kenya (Robertshaw, 1991). Fewer sites are reported for other regions, with the areas west and southwest of the Serengeti National Park having received only limited systematic study (Mabulla, 2005), and the park itself yielding few published sites (Bower, 1973; 1976; Bower and Chadderdon, 1986). Some sites provide evidence of intensive land use (Stump, 2006) and other regions have limited material evidence due to extensive land use practices, commonly yielding ephemeral surface scatters rather than clearly bounded dense artefact concentrations. Some studies have begun to redress this balance (Foley, 1981; Masao, 2015; Githumbi et al., 2018a; Shoemaker, 2018).

The complexity of the archaeological record coupled with the diversity of ecosystems and livelihood strategies have discouraged spatial interpolations between known sites to create spatially continuous palaeodemographic maps. A range of economic strategies are represented over the past 6000 years and understanding the complexity of livelihood strategy variation and impacts on landscapes remains a key area of research. Targeted survey work and selective excavation of key sites coupled with new modelling approaches are needed. For example, land use categorisation and mapping approaches aggregate available knowledge and have been applied across West Africa (Kay and Kaplan, 2015; Hughes et al., 2018; Widgren, 2018; Kay et al., 2019). A further step would be to develop historical land use and land cover maps for the borderlands to motivate land management and policy formulation discussions.

A significant portion of archaeological research in the region has been directed toward the development and spread of food production systems - the two key narratives being the southward expansion of livestock production along the conduit of the Rift Valley (Marshall, 1990; Marshall and Hildebrand, 2002) from c. 4800 BP and possible disease barriers (Chritz et al., 2015; Gifford-Gonzalez, 2017), and the dispersal of crop cultivation following its establishment in highlands west of Lake Victoria (van Grunderbeek, 1992) around 2500 BP. The former is largely reconstructed through analyses of faunal remains from archaeological sites, ranging from traditional species quantifications (Robertshaw, 1991) to stable isotope analyses (Chritz et al., 2019) and genetics (Skoglund et al., 2017; Prendergast et al., 2019a,b). The latter draws frequently on perceived associations between farming and certain forms of pottery (van Grunderbeek, 1992; Stewart, 1993) rather than the direct evidence offered by archaeobotany (e.g. pollen grains recovered from archaeological contexts) and, in later periods (e.g. later second millennium CE), evidence of large-scale landscape manipulation in the form of terracing, wall-construction and irrigation (Stump, 2006; Stump and Tagseth, 2009; Onjala, 2003; Lang and Stump, 2017). A common theme in these studies is the shifting and fluid social and geographical boundaries that existed between land use practices in the borderlands: whether herding, hunting or farming (Lane, 2004).

3.3. Humanities and social sciences

Anthropological, ethnographic, sociological, and historical linguistic studies contribute knowledge of socio-ecological systems and human-environment interactions (Ellis et al., 2016). Social scientific enquiry elucidates the potential for understanding historical, present, and future anthropogenic drivers of LULCC, as well as stakeholder perceptions of change and its drivers. Furthermore, combining qualitative and quantitative approaches can cross-corroborate lines of evidence of human-environment interactions and frame solutions-based research on socio-ecological topics (Kopnina and Shoreman-Ouimet, 2013). Social scientific enquiry provides critical analysis of the arguments, actors and agents involved in LULCC public policy debates. Arguments of the spatiality of policy goals, advocacy by different stakeholders, and the trade-offs necessary between conservation, traditional land use, and economic development goals (Howe et al., in press) are some examples of the complementarity of quantitative and qualitative research.

Several anthropological and ethnographic studies synthesise multiple evidence streams to assess human land use patterns in northern Tanzania (Fig. 5). A 2000-year history of socio-ecological systems was developed from oral histories about life in western Serengeti corroborated with historical linguistic, archaeological and documentary evidence (Shetler, 2003, 2007). Questionnaires and interviews were used to examine the seasonal timing, location and purposes of fires set by communities and understand the spatiotemporal patterns of human agency behind fire regimes in Chyulu Hills and Engikareti (Butz, 2009; Kamau, 2013; Kamau and Medley, 2014). Results from these types of studies have strong potential to connect with vegetation models to resolve human contributions to fire regimes and environmental outcomes. Oral histories and ethnographic data have been combined for analyses of contemporary and historical responses to drought and household decision-making processes (Miller et al., 2014) and to determine generational differences in perceptions of wellbeing (Woodhouse and McCabe, 2018). A large resource of relevant social science literature could be collated and synthesised as an early step toward integrating qualitative and quantitative data concerning the borderlands. Understanding how social constructs manifest in LULCC is crucial to developing land management regulations for environmental futures and exploring coupled socio-ecological legacy effects and trajectories.

3.4. Documentary, archival and historical sources

Several LULCC-relevant studies making use of primary sources stored in libraries, repositories and archives, come from historically-oriented disciplines (historical geography, historical cartography, political ecology, institutional history, and environmental histories). Studies have used historical cartography, digitisation of land cover and land use maps, to analyse socio-ecological patterns at various scales including subnational (Willcock et al., 2016), regional (Sunseri, 2013), and continental (Aleman et al., 2018) assessments. Few collations and critical syntheses of LULCC have used historical cartography combined with documentary evidence derived from accounts of early European missionaries, explorers and sport hunters (Sinclair, 2012), but there are examples from elsewhere across eastern Africa (Börjeson et al., 2008; Börjeson, 2009; Mitchell, 2011; Mitchell et al., 2006). Creating archives, whether documentary, oral transcripts, photographic, or cartographic, is selective (Hamilton et al., 2002; Pickles, 2004; Burton, 2006; Kitchin et al., 2013; Morton and Newbury, 2015; Abrams, 2016) and particular attention has been directed to colonial archives and how these silence certain perspectives (Stahl, 2001; Stoler, 2010). There is also growing recognition that these gaps and biases reveal important information and insights that are as crucial as the archived records themselves.

Oral and documentary sources of precolonial and early colonial histories describe settlement and land use patterns (Lamprey and Waller, 1990; Shetler, 2007). Observations by Anglo-German Expeditions and cartographers provide valuable records of Serengeti socio-ecology prior to, during, and following the nineteenth century experiences of peak ivory trading, slave trading and Rinderpest epidemics (Wakefield, 1870, 1882; Farler, 1882; Baumann, 1894; Smith, 1907; Rempel, 1998; Kelly, 2014; Sinclair et al., 2015a,b); yet require critical analysis from an LULCC perspective. The interactions between herbivores and vegetation cover mediated by anthropogenic changes over the course of the precolonial to independence timeframes have important implications for historical and future socio-ecological trajectories (Ford, 1971; Waller, 1990; Sinclair et al., 2008a,b, 2015a,b) and require further multidisciplinary investigations to improve relevance for management.

LULCC dynamics are also elucidated through studies of environmental policies. Local ruling elites, colonial authorities, post-independence governments and non-governmental institutions have used policy instruments and interventions to extend and reinforce power into marginal areas by leveraging natural resource use (Conte, 2004; Hökansson and Widgren, 2007; Sunseri, 2009; Mapedza, 2010; Hodge, 2011) or influencing access to natural capital (Chuhila, 2016; Chuhila and Kifyasi, 2016; de Bont, 2018; Boles et al., 2019). Political ecologies of cattle production and destocking show that the long history and patterns of beef industry industrialisation have had effects on the landscape, people and ecology of Tanzanian savannahs (Sunseri, 2013). The political ecology of forestry and the efforts of globalised conservation, scientific management, resource governance, and forestry industrialisation have also had profound ecological effects and pervasive impacts on how power and governance of land and resources are negotiated from local-to-national and global levels (Sunseri, 2009; Green and Friis Lund, 2015). Both the beef and forestry industries connect rural areas to global economies and continue to be important realms for potential land cover and land use change and socio-economic power relations. Historical food production and lumber extractions and export actuary tables have yet to be investigated to examine agroforestry land uses and intensities, to characterise historical vegetation, labour estimates, actor networks or trade connectivity.

Perspectives on institutional histories of protected area creation and LULCC impacts are themes highlighted in autobiographies and memoirs of contemporary travellers, employees and settlers. Material such as Bernhard Grzimek's 1959 *The Serengeti Shall Not Die* documentary and accompanying book (Grzimek and Grzimek, 1960) were notably influential (Neumann, 1995; Kideghesho et al., 2005; Beinart and McKeown, 2009; Lekan, 2011; Boes, 2013). One set of historical studies focuses on the timing, context, and actors involved with establishing protected areas (Richter, 1994; Homewood, 1995; Neumann, 2002); including Serengeti National Park (Neumann, 1995, 2003; Sinclair, 1995, 2012), Tarangire National Park (Davis, 2010; Årlin, 2011), Ngorongoro Conservation Area (Århem, 1985a), and Mount Meru and Arusha National Parks (Neumann, 1992, 1994). There are no similar studies of the Maasai Mara Game Reserve and no critical institutional histories or visual anthropological studies for infrastructure development and or NGO projects, which have a strong potential to provide LULCC insights over the past decades to century. A second strand of studies examine gazetting in broader comparative historical perspectives (Collett, 1987; Knowles and Collet, 1989; Århem, 1985b; Neumann, 2003) and document the changing patterns of conservation, land fragmentation and wildlife management approaches (Charnley, 2005; Galvin et al., 2008: Kaltenborn et al., 2008; Goldman, 2011; Goldman and Riosmena, 2013; Bluwstein, 2018). A considerable amount of media (photographic, videographic and cartographic material) exist to reconstruct LULCC changes with a strong potential for relevance and meaning in land management discourses.

3.5. Stakeholder perceptions and future expectations

People's perceptions and expectations of LULCC patterns collected through questionnaires, interviews, focus groups, and even artistic expressions are analysed using qualitative research methods (Anana and Nique, 2010; Schreier, 2012; Leal Filho et al., 2017). Future and retrospective stakeholder perspectives on LULCC benefit from established methodologies (Sardar, 2010; O'Brien, 2012) and are combined with public, practitioner and expert knowledge for producing outputs relevant to support LULCC management decisions (Miller et al., 2014). Exploring scenarios of potential futures is a philosophical and pragmatic exercise in exploring modal narratives of (im)possibility, necessity and contingency (Booth et al., 2009), which connect with retrospective data and model projections. Generating scenarios in itself is a form of synthesis and an active example of science-policy integration. Inclusivity and exclusivity issues need to be assessed when directly engaging with stakeholders. Participatory approaches to scenario development are active tools for facilitating evidence-based decision-making by combining different thematic dimensions and temporal and spatial scales with high viewpoint diversity.

Participatory research assessments of perceptions of climate change impacts by subsistence-oriented communities examine several spatial scales of human-environment interactions (Vervoort et al., 2013; Savo et al., 2016), and assess vulnerability and mediating effects of local ecological knowledge on adaptation and resilience for informing policy interventions. Multi-stakeholder studies require analyses of the role powerful actors and institutional stakeholders have in shaping environmental policy discourses and the manner in which this may foreclose certain perspectives and approaches (Adams et al., 2004; Gardner, 2017; Hissen et al., 2017; Armstrong and Brown, 2019). Participatory frameworks are increasingly used for planning in place-based social-ecological research (Oteros-Rozas et al., 2015) and are encouraged for biodiversity and ecosystem services assessments (IPBES, 2016; Kok et al., 2017). A novel framework for integrating participatory approaches with spatial modelling to produce quantitative scenarios of the impacts of alternative socioeconomic and policy trajectories was applied to explore land use and ecosystem service changes across East Africa (Capitani et al., 2016, 2019a, 2019b). Regional-scale scenarios were developed by engaging local stakeholders in assessing land use changes for eastern Tanzania, including Eastern Arc Mountains (Swetnam et al., 2011) and for smallholder farmers in South Pare (Enfors et al., 2008). Local-scale scenarios have explored how communities bordering the southwest areas of Serengeti National Park would respond to the reintroduction of painted dogs (*Lycaon pictus*) (Masenga et al., 2017). This long-ranging predator uses many land use and cover types (Masenga et al., 2016) and threatens livestock through depredation and as a disease vector; yet, is integral to ecosystem functioning (Gascoyne et al., 1993; van de Bildt et al., 2002). Emerging work gives greater emphasis to issues surrounding land tenure, livelihood security and establishing relations of trust and respect between different stakeholders (Davis and Goldman, 2019). Qualitative techniques and outputs can be integrated with computer modelling frameworks to analyse patterns of community and stakeholder perceptions and expectations of land and environmental change (Lesorogol and Boone, 2016). Ecosystem services modelling frameworks such as InVEST and ARIES are often used to link environmental processes with societal behaviours, and used to evaluate environmental and socioeconomic outcomes and support decision making (Christin et al., 2016).

3.6. Earth observation and socio-environmental monitoring

Empirical measurements of Earth systems provide detailed information covering the recent past across local-to-global scales. Earth observations monitor a wide range of phenomena: meteorological to ecological, water quality, lake levels, river flows and many more, yielding datasets on natural and anthropogenic processes. Combining several forms of observation products strengthens such approaches and adds complementary perspectives (Pohl and Van Genderen, 1998) with further compatibility with other types of Earth systems data. For example, Verschuren et al. (2000) combined historical field-based lake level measurements with sediment derived palaeoecological data to understand long-term processes affecting a freshwater system in Kenya. Willcock et al. (2016), combined ground-based measurements of carbon, with historical maps and remotely-sensed products to examine carbon emissions and land use changes. A preliminary summary survey of available earth observation products and data identified in the literature review is presented in SM4.

3.6.1. Remote sensing

Earth observation through satellite-based sensors provide unprecedented measurements and products at multiple spatio-temporal scales. Since the 1960s, satellite imagery has captured land cover variations at variable spatiotemporality resolutions, spectra, and ground coverage. Remotely sensed land cover products are used to derive maps of ecosystem services to characterise and evaluate the spatiality of socio-ecological interactions (Kariuki et al., 2018a). Satellite-based meteorological observations and optical and multispectral imagery are commonly available products; for example, the Tropical Rainfall Measurement Mission (TRMM) and Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) (Andreae, 2004; Winker et al., 2007; Funk et al., 2014). Sporadic air photography began during the 1930s and systematic coverage of northern Tanzania and southern Kenya dates from the 1950s, with repeated photography over subsequent decades. Additional imagery has also been captured at various times by contract to private companies for development and wildlife census (e.g. Sanya, 2008). Air photography libraries in Kenya and Tanzania archive the original photographs and there are sets available in the UK (Bodleian Library, Oxford and National Collection of Aerial Photography, Edinburgh). Since the launch of Landsat in 1972, a sequence of satellite imagery is available with increasing frequency and spatial resolutions. MODIS imagery and observations track fire activity since 2001 to present and have been used to develop products including a pyrodiversity index representing the variation in savannah fire regimes (Hempson et al., 2018; Beale et al., 2018; Andela et al., 2019). The European Union's Earth Observation Programme Copernicus through the Land Monitoring Service (CLMS) provides free access to high resolution spatial data and global products to improve sustainability and efficiency of land use. The GMES & Africa Programme (jointly between African Union and European Commissions) specifically addresses African stakeholder needs for land management decisions (http://gmes4africa.blogspot.com). Government and private sector initiatives making high-resolution imagery and web-based map services available to researchers are useful for co-developing research questions and integration between imagery producers, custodians and users (Kwok, 2018). Such partnerships broaden the use of these products and ensure plurality in stakeholder engagement in research and policy development agendas.

Multiple studies have included Earth observation products to assess trajectories and rates of recent LULCC at decadal and multiannual resolutions (Shilling, 2013; Detsch et al., 2016; Mwaura et al., 2016; Higgins, 2017; Mmbaga et al., 2017; Higgins and Caretta, 2019; Kilungu et al., 2019), correlations between changes in settlement distributions, vegetation and wildlife densities (Homewood et al., 2001; Sernels et al., 2001; Lamprey and Reid, 2004; Ogutu et al., 2009), and trends in deforestation and agricultural expansion (Mwangi et al., 2018). There are also unpublished theses that contain analyses of remote sensing data (Msoffe, 2010; Snider, 2012; Lariu, 2015; Fox, 2017) that require critical synthesis. The scale of remote sensing studies varies, focusing on characterising changes to single wetlands over the past few decades (Seki et al., 2018) or larger lake or river catchments (Bachofer et al., 2014; Mwangi et al., 2018). McNaughton (1979) presented a comparison of air photographs taken in 1959 and 1968 showing changes in woody thickets at Bologonja spring, Serengeti National Park. Muriuki et al. (2011) combined repeat air photographs from 1967 and 1978 with satellite images from 1999 and 2001 to examine patterns of land cover change in community areas on the eastern slopes of Chyulu Hills, Kenya. Recent LULCC surrounding the Greater Serengeti Ecosystem has been characterised using satellite imagery (Niboye, 2010; Estes et al., 2012; Probert et al., 2019; Veldhuis et al., 2019a). Mixing several types of remote sensing products at varying scales strengthens the utility of these studies to inform management and policy decisions and visualisations improve usefulness for non-expert stakeholders (Baynard, 2013).

3.6.2. Sensor-based and ground-based observations and monitoring data

Meteorological data are available through the Tanzania Meteorological Agency, Kenya Meteorological Department, and the World Meteorological Organization (members since 1962-09-14 and 1964-06-02 respectively). Weather station data from research networks exists within Serengeti National Park (Sinclair, 1979b; Wake Forest University) and across transects of Kilimanjaro (Schüler et al., 2014). Meteorological data aggregated into spatiotemporal products are available covering several scales, such as 1 km^2 monthly WorldClim climate data using a 1970–2000 reference (Fick and Hijmans, 2017). The volcanic history of the region has shaped much of the landscape and several volcanoes have the potential for impactful events and modify LULCC (Hay, 1989; Dawson et al., 1995; Dawson, 2008). Emissions and ashfall events continue to occur at Oldoinyo Lengai (Keller et al., 2010) and basalts around Chyulu Hills forming barren or sparsely vegetated lava fields date to as recently as the past few hundred years (Saggerson, 1963; Williams, 1972). Ecological recovery following volcanic activity and land uses on impacted terrain have been insufficiently investigated but can be tracked through chemical analyses of ash layers in lake sediments, for example.

Ecological monitoring emerged from observing the early Rinderpest epizootic impacts on cattle and wild ruminants which erupted several times in the 1890s, 1917–1918, 1923, and 1938–1941 (Sinclair, 1979a; Shetler, 2007). Rinderpest monitoring continued (Plowright and McCulloch, 1967; Taylor and Watson, 1967) and is ongoing in Tsavo, Kenya, but the disease has been largely eradicated across the borderlands area (Njeumi et al., 2012) and systematic wildlife monitoring in protected areas developed from observing ecosystem recovery throughout the twentieth century. This frequently combines several quantification methods. Local socio-ecological knowledge was important to containment efforts, such as cattle exposure and immunity, but was also counterproductive through cattle-wildlife transmission of low-virulence strains associated with long-distance pastoralism (Kock et al., 2006; Njeumi et al., 2012; Roeder et al., 2013). Recovery of herbivore populations and human populations were major drivers of changing vegetation patterns, most conspicuously in savannah woody and grassy structure distributions, tsetse fly abundances and distributions, fires, nutrient redistribution, and human population distributions (Waller, 1990). The recovery trajectories of large herbivores in Serengeti was observed by wildlife counts beginning as early as 1958 and 1961 (Sinclair, 1979c) and continue to present. Increasing herbivore populations in SNP reduced the area burned, with above ground grass biomass consumption changing from fire to grazing dominated (Norton-Griffiths, 1979; Archibald and Hempson, 2016), with consequences for changes to soil, vegetation cover, and trophic cascades (McNaughton, 1985; Archibald, 2008; Donaldson et al., 2018). Wildlife monitoring of conservancy lands show that ungulates make trade-offs between feeding, drinking and human land use and predation risks, which highlights the potential sensitivity to hydroclimatic and land use changes (Anderson et al., 2010; Schuette et al., 2016; Veldhuis et al., 2019b). Synthesis information on vegetation changes dominantly are available from the Serengeti ecosystem which hosts several long-term vegetation plots (Serengeti book series I to IV and references therein). Human activities related to development (construction, road maintenance, ornamental plants, refuse dumping and water abstraction) introduce exotic plant species (John et al., 2017). Several key ecosystem components have yet to be fully explored; such as vegetation change studies in kopjes, highlands and wetlands. While there are relatively few invasive species in the park there is considerable pressure from outside the park with a strong potential to initiate or accelerate impactful changes in vegetation cover and composition (Witt et al., 2017).

3.6.3. Data on population dynamics

Longitudinal datasets of social and institutional systems are a rich source of human and cultural dynamics that come from many sources with different scales or spatiotemporal explicitness, for example, census data (Pallaver, 2014), settlement patterns (Lamprey and Waller, 1990; Lamprey and Reid, 2004), economic indicators, market analyses, land purchasing (Harding and Chamberlain, 2016), environmental degradation and demographic change (Warner et al., 2010). These data are dispersed (Kenyan and Tanzanian National Bureau of Statistics), with different accessibility and data qualities, and require bespoke methods to assemble for further analyses using other LULCC data to examine trajectories of change. Recent applications of Earth Observation datasets have converted census tabular data into spatial products of population distribution harmonised across national borders to deliver realistic estimates of population dynamics and spatial patterns. The Gridded Population of the World (NASA Socioeconomic Data and Applications Center SEDAC), the Global Human Settlement-Population Grid (European Commission - Joint Research Centre (JRC)), and the WorldPop program use the same census data sources but different ancillary datasets and modeling approaches to deliver population and demographic indicators change over the past decades using online tools and open data (see the comparison webservice https://sedac.ciesin.columbia.edu/mapping/popgrid/#).

3.7. Computer modeling outputs and products

Numerical models with spatially explicit input data and defined rules produce spatially-explicit outputs of LULCC (Boone et al., 2011), which can then be used in combination with other data and model products. Novel conceptual and modeling techniques make use of coupling land use and land cover classifications with other types of socio-environmental models (Kay and Kaplan, 2015; Klein Goldewijk, 2017) and integrating methods and knowledge from social sciences (e.g. valuing ecosystem services, Kariuki et al., 2018a). Coupling multiple models provides methods of representing the interaction between people and their environment while incorporating spatial heterogeneity (Bithell and Brasington, 2009). In addition, multiple time intervals of analysis permit estimates of rates, directions, and types of changes that have occurred (Funk et al., 2008; Alcamo et al., 2011; López-Carr et al., 2014; Shukla et al., 2014) with example studies available for West Africa (Kay et al., 2019). Of particular interest are models with the ability to investigate retrospective trends and that produce projections of potential futures or that permit harmonisation between historical and future model inputs (e.g. Frieler et al., 2017). Data-data and data-model comparisons, as well as model-model intercomparisons are key sets of research frontiers for combining retrospective, contemporary and future projection products to explore and support decision making.

Global LULCC future projection models suggest high possibilities of changes in pasture, forest and cropland, but moderate to high disagreement exists between models for eastern Africa (Prestele et al., 2016) due to complex interactions between biophysical and socio-economic factors. Two retrospective global reconstructions of land cover, land use and human population estimates are available: HYDE (Klein Goldewijk et al., 2010, 2017) and KK10 scenarios (Kaplan and Krumhardt, 2011; Kaplan et al., 2011) - both span 10,000 years BP to present, although uncertainty vastly increases earlier than 2000 years BP. Palaeoenvironmental data are not directly incorporated in these models but are useful for comparisons and to inform spatial downscaling. Analyses across modern national borders are difficult because of compatibility problems within the underlying data used in developing hindcast demographic data. For instance, KK10 products show a clear difference in land-use intensity for all time periods prior to CE1850 across the current Kenya-Tanzania border (Kaplan and Krumhardt, 2011) with the now-Tanzanian side appearing underestimated (Fig. 6). This arises from inconsistent historical census methodologies and varying spatiality, thus more integrated modeling is necessary to improve outputs. Conceptual models of human extensive and intensive land use work in combination with new computational methods and techniques for integrating palaeoenvironmental and archaeological datasets (Kay and Kaplan, 2015; Hughes et al., 2018). Statistically downscaled Regional Circulation Models are more relevant for management decisions over global circulation model projections (Platts et al., 2015). Multiple global vegetation models are available for the region, notably static and dynamic global vegetation models, which are used to project the potential effects of climatic change and human disturbances on vegetation distribution. Coupling projected climate models with species distribution models explores potential species distribution changes, presence/absence and interactive effects of biotic and abiotic elements (Platts et al., 2010).

Static models provide a tool for converting past vegetation into palaeoclimatic patterns (Haxeltine and Prentice, 1996; Cramer et al., 2001) and include BIOME models (Prentice et al., 1992), while dynamic global vegetation models (DGVM) capture transient responses of vegetation distribution and processes to changing climates (Cramer et al., 2001; Sitch et al., 2003; Bond et al., 2005). Existing dynamic global vegetation models differ in their degree of complexity and suitability for different tasks. For example, the Sheffield DGVM is used to investigate and compare the impact of fire and climate in driving the distribution of vegetation globally (Bond et al., 2005) and to demonstrate changes in global woody biomass in long-term savanna burning experiments (Bond and Keeley, 2005). The adaptive DGVM specific to savannah ecosystems has been used for studying tree-grass interactions in African savannas (Scheiter and Higgins, 2009; Higgins and Scheiter, 2012). The Lund-Potsdam-Jena General Ecosystem Simulator (LPJ-GUESS: Smith et al., 2001; Sitch et al., 2003) has been used to produce coupled data-model analyses of mid-Holocene and present biome distributions in eastern Africa (Fer et al., 2016) and to project futures (Fer et al., 2017). Additionally, coupled LPJ-GUESS and agent-based models for eastern African rangelands suggest that hydroclimate variability and conservation regimes are key in shaping land use patterns and herbivory (Kariuki et al., 2018b). Biophysical models, including Savanna Dynamics (Holdo et al., 2009) and SAVANNA (Boone et al., 2002) further connect vegetation and herbivory dynamics. SAVANNA has been linked to an agent-based model and used to explore pastoral household wellbeing in response to droughts in southern Kenya (Boone et al., 2011). Other models for southern Kenya have explored the potential of payment for ecosystem services to promote conservation land uses (Bulte et al., 2008) and the impacts of land subdivision on livestock numbers and pastoral households (Thornton et al., 2006). The Fire Model Intercomparison Project (FireMIP) envelopes many fire models and connects dynamic vegetation models to understand drivers and consequences of changing patterns of fire on the globe (Hantson et al., 2016; Rabin et al., 2017). Population models have been developed and used by international organisations (FAO, UNEP, UNDP; Bhaduri et al., 2002). Meteorological products are available covering the area of interest, with the most commonly used being the NCEP/NCAR reanalysis global products with historical weather and meteorological products since 1 January 1948 to the present (Kalnay et al., 1996; Anyah et al., 2006).

3.8. Syntheses studies and integrated landscape analyses

Synthesis studies summarise research within a single discipline (e.g. archaeology, Prendergast, 2011) or across several (Marchant

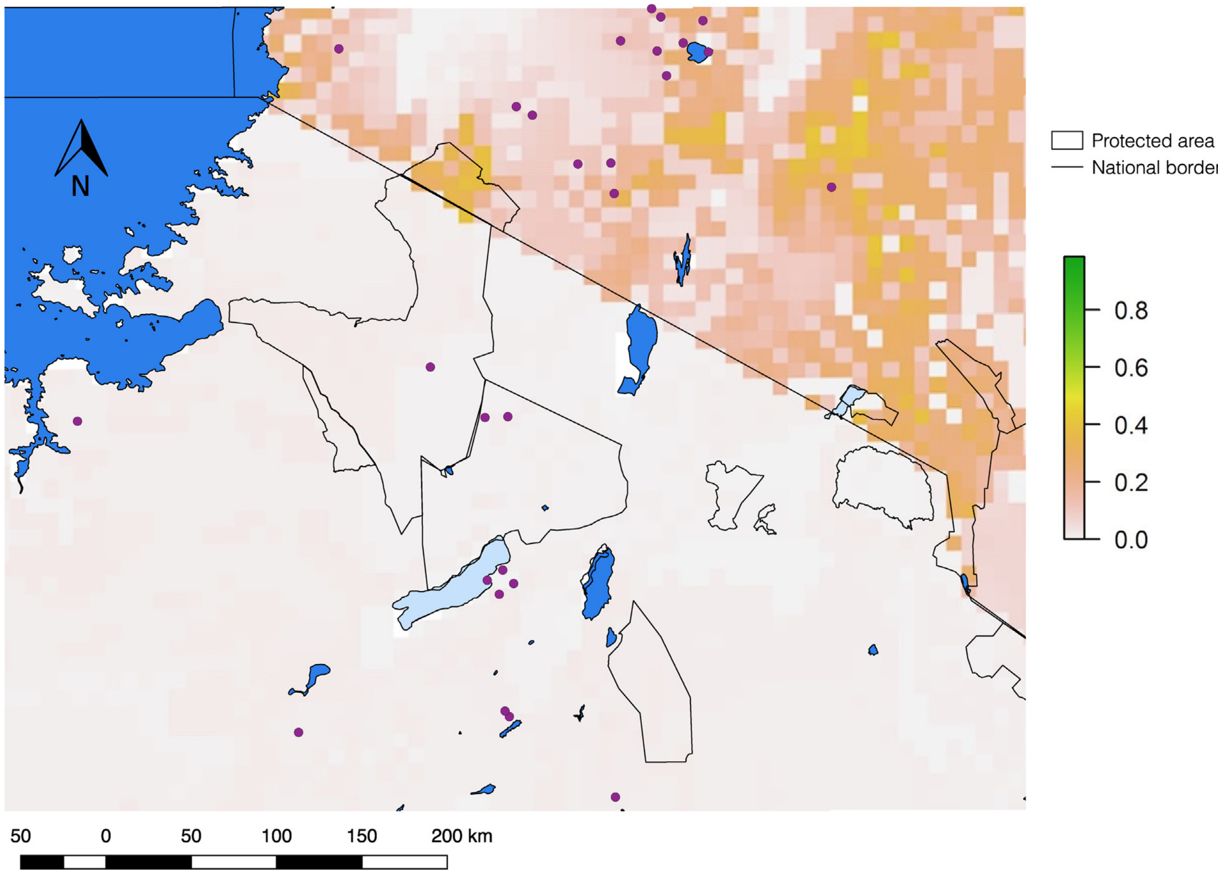

Fig. 6. A retrospective projection of land-use intensity in the study area at 2000 cal yr BP according to the KK10 land-use model (Kaplan and Krumhardt, 2011), with archaeological sites dating 6000-2000 cal yr BP (purple circles; Marchant et al., 2018). Scale shows the fraction of each grid cell under anthropogenic land use. Note the disparity between reconstructions for Kenya and Tanzania, which contrasts with archaeological evidence for human land-use intensity. The visibility of the modern national border as an artefact in the projection is related to inconsistencies in historical population estimates used to generate existing land use scenarios.

et al., 2018) and garner assessments of data quality, biases and uncertainties (Boyd, 2013). The source materials draw from academic peer-reviewed papers and books, but also include forms of grey (white papers and reports) and popular science literature (essays, biographies and institutional histories). To date, conceptualisations of transdisciplinary approaches guide project development from an academic stakeholder perspective (Willis et al., 2007; Rull, 2010; Gillson and Marchant, 2014; Seddon et al., 2014; Reed et al., 2016; Kaufman et al., 2018) and it remains difficult to assess reporting of case studies, successful cases of implementing integrated approaches, and to evaluate outcomes (Reed et al., 2017).

The Serengeti book series aggregates many datasets and publications relevant to LULCC (Sinclair, 1979a; Sinclair and Norton-Griffiths, 1979; Sinclair and Arcese, 1995; Sinclair et al., 2008a,b, 2015a,b) and Hamilton (1982) summarises Quaternary vegetation in eastern Africa. The Serengeti book series assemble decades of ecological research and increasingly have focused on human-environment interactions and anthropogenic topics as drivers of ecological change and the complexity of public stakeholders and protected area management. Autobiographies summarise major advances in savannah ecology, the life experiences of researchers in Serengeti, its political ecology, and institutional history of the Greater Serengeti Ecosystem (Turner, 1978, 1988; Sinclair, 2012). Shetler (2007) provided a synthesis of oral histories including human-environment interactions of the western Serengeti region over the last 2000 years with an emphasis on precolonial times to present. Multiple regional archaeological syntheses have also been presented (Ambrose, 1982; Mabulla, 2005; Prendergast, 2011; Lane, 2013) and Marchant et al. (2018) assembled a multidisciplinary synthesis of palaeoenvironmental, archaeological, and modeling studies of late Holocene LULCC. Willcock et al. (2016) produced estimates of LULCC trajectories and impacts on carbon in Tanzania by combining several historical maps (1907–2000) and remote sensing products with local measurements of carbon storage. The results showed the effectiveness of protected areas at reducing land cover rates of change and demonstrate that additional data types could be used to extend these types of analysis further back in time and to incorporate socio-ecological data.

Synthesis studies promote familiarity and integration of several disciplines into public policy discourses for LULCC policy formulation and thus, the role of knowledge within those debates (Kaufman et al., 2018). Overcoming barriers and challenges related to data archiving (Wilkinson et al., 2016), transparency and access require solutions for uptake by non-academic stakeholders and open further academic advancements. In order to be incorporated into a knowledge pillar that is useful and meaningful to decision support, scientific data quality, robustness and lifecycles need to conform to evidence-based policy requirements set in principles-based frameworks. A conscious effort to develop syntheses for multiple audiences and to co-develop syntheses with stakeholders improves relevancy and meaning within LULCC dialogues and reliability for supporting policy and justifying decisions.

4. Considerations for future research projects

This knowledge map of evidence types available for the borderlands, the array of disciplines and methodologies, how they have been used, and relevant published synthesis studies, is presented from academic perspectives on anticipated needs for evidence-based land management support in the region. The collation and synthesis of data into usable formats is an academic step expected by end users of LULCC knowledge from outside of academia. Assembling LULCC knowledge synetheses prepares interdisciplinary researchers as a foundation for extending LULCC research authority (*sensu* Gieryn, 1983), usefulness and accessibility, as well as improving integration and co-production of research across the science-policy interface. Table 1 explores some of the opportunities and challenges related to each evidence stream with some example studies from the literature review and broader relevant discourse on LULCC research. Socio-ecological changes, driven by climatic, local, or anthropogenic factors potentially initiate or exacerbate debates in contested places (Anderson and Lochery, 2008; Shanguhyia and Koster, 2014) and are superimposed upon ecological legacies and long-standing narratives (Koning and Smaling, 2005; Boles et al., 2019). It is important to avoid solely basing policy interventions on arguments of environmental degradation and move toward also addressing issues of unequal access to resources and the wider political economy of natural resource management (Smucker et al., 2015).

4.1. Reframing a research culture that extends to the science-policy interface

Calls to address land management challenges (Shetler, 2007; Watson et al., 2014) emerge because current strategies frequently have had limited success as evidenced by questions of accessibility and exclusion and competition between strategies, which interlink with broader processes of population pressure increases, low education indices, increasing inequality and challenges for redistributing benefits from resource extraction/use. Climate change adaptation and mitigation initiatives have been identified in high-level development policies, but implementation and measures of success are patchy at local scales. Yet, most broad-scale sustainability targets either remain unmet or appear challenging to achieve with current technology, institutions, and behaviours (Rockström et al., 2009). Several landscapes across the Tanzania-Kenya borderlands have been intensively researched from diverse academic perspectives, yet, many factors remain underexplored including uncertainties, contradictory assessments, and emerging challenges that influence land-use planning and management. We contend this is partly because there is little synthesised knowledge of environmental, social and heritage interactions at landscape or operational scales (10s-10,000 s km^2) of sufficient temporal depth (extending decades to millennia), in digestible and tractable formats communicated to broader audiences (Jackson, 2007; Kruger, 2015; Kaufman et al., 2018). There are deficiencies in appreciating the usefulness of antecedent data to planning sustainable futures (Birks, 2012) and in effectively articulating the relevance of long-term socio-ecological knowledge between the scientific community, policy formulators and public stakeholders (Seddon et al., 2014; Armstrong et al., 2017). Analyses combining diverse insights generate balanced assessments (Schindler et al., 2016) and consensus-building opportunities because the various foci presented by each stakeholder leads to different perspectives on the co-benefits of land-use policy outcomes (e.g. Howe et al., in press). Additionally, most of the academic-generated information does not account for interdisciplinary approaches, thereby limiting the capacity for findings to be effectively integrated into policy and practice (Reid et al., 2016). As such, scale mismatches compound challenges because evidence from ‘bottom-up’, fine-scale, studies can potentially be aggregated inappropriately and because downscaling global academic assessments lack sufficient detail and integrated information relevant to usefully inform national- and local-scale planning. Any form of data inaccessibility or black-box methods precludes reliability in LULCC public policy formulation and implementation.

4.2. The LULCC knowledge, values and rules pillar nexus

The three pillars that form the decision context overlap and interact in LULCC public policy formulation (Gorddard et al., 2016; Figs. 1 and 7). Addressing complex challenges manifested by rapid climate, environmental, policy and livelihood changes and exploring the ensuing trade-offs between goals in socio-economic development and environmental sustainability in the region encourages new frameworks for envisioning and planning desirable futures (Fokou and Bonfoh, 2016; Galvin et al., 2018; Reid et al., 2016). Combining physical sciences, with its tendency toward quantification and prioritization of the biophysical (climate, ecology, geology), with social sciences and humanities balances the research, encapsulating the dynamism of human agency and the role of cultural systems as key features of socio-ecological sustainability (Davidson, 2010). Cultural values influence the decision making processes, and consequently, changes in culture are likely to shape socio-ecological interactions. Consequently, human values and choices influence both environmental and societal resilience. How this plays out depends on the interactions with the environment at a given time (Bollig, 2014) and human-environment relations should be considered to always be recursive in nature; thus, landscapes are always in a state of constant ‘becoming’ (Ingold, 1993). Without totally ignoring basic research, LULCC researchers should co-design projects to internalise the constant dynamics and variety of perspectives, explicitly improving usefulness and relevance to more stakeholders and to build community confidence in research activities and outputs. This requires well-supported and transparent syntheses and data archiving by researchers in support of public use, evidenced-based public policy formulation, and legal and regulatory requirements that have their foundations based on evidence. Strengthening the knowledge pillar benefits all pillars of consideration for LULCC decision making.

4.3. Beyond conventional academic sources

Many LULCC future foresight tools and information exist and are continuously being developed and more frequently used outside of the academic sector. Spatiotemporal datasets on policy regimes, land tenure and global trading exist in a plethora of accessibility levels and formats but requires concerted effort to develop links and interoperability. There is a need to think creatively about what material might be available and the research efforts needed to access this. Emerging research approaches from academia are enhanced by strong links with non-academic partners (like museums and NGOs), especially efforts that require engagement and commitment from the public (e.g. Webb et al., 2010; White, 2012; Berger, 2017; Fritz and Fraisl, 2018). The use of Big Data and computer learning methodologies to mine the web and social media for relevant texts and images, sometimes referred to as web-scraping (Munzert et al., 2014), should be used to investigate LULCC and future trajectories (Marres and Weltevrede, 2013; Viotolo et al., 2015). Likewise, geo-explicit deep dive search engines collate relevant information from all media sources to examine environmental changes (Niu et al., 2012; Zhang et al., 2013; Peters et al., 2014; Callaway, 2015). Repeat photography embedded within citizen science frameworks has produced

Table 1
Scientific approaches to multidisciplinary investigations of land use and land cover change trajectories in eastern Africa.

Evidence stream	Approach	Challenges	Benefits	Unexploited potentials	Solutions	Example studies
Community perceptions and expectations	-Questionnaires -Interviews -Focus groups -Artistic expressions -Content analyses	- languages, translations - Quantification - Demographic distributions -Access, Permissions -Engagement -Nested scales -Consent from public -Permits to contact government employees -Payments	-explicit land uses -perceptions of change -identification of values -perceived relative importance of change -Expectations of future	-Voice of marginalized groups, women, children -Identifying flows (monetary, non-pecuniary, ideas, power, commodities)	-New socio-ecological modelling techniques -Continued engagement -knowledge exchange -continuous dialogue -Academic-NGO partnerships	Shetler, 2007; Capitani et al., 2016
Computer modelling	-Social models -Ecological models -Environmental models -Coupled models	-constraining uncertainties -specialist skillsets -how to incorporate data into models? -data-model comparisons rely on several expert groups working together	-exploration of hypotheses -retrospective and future projective -Africa-specific DGVM models exist -Savanna-specific models exist	-data-model comparisons -educational outreach -exploring scenarios with policy interface	-transdisciplinarity -multi-audience communication	Kaplan and Krumhardt, 2011; Platts et al., 2015; Klein Goldewijk et al., 2017
Environmental monitoring	-Measurement monitoring (ex. Meteo, moisture) -repeat plot studies -field experiments and manipulations -species counts	-lack of committed funding support -short-term operations -fine geographic scales -detection limitations -patchy data -varying methodologies -different metrics -data accessibility -collaboration and authorship -ownership -complex institutional landscapes -limited data validation and replication	-high temporal resolution -high taxonomic resolution	-data-data/ data-model comparisons -communications and growth between research communities	-FAIR -open access -increased interdisciplinarity	-Sinclair, 1979c; Funk et al., 2014
Earth observation	-Satellite products -Multispectral -Multi-messenger -Air photographs -Repeat photography	-Geomatics expertise in high demand -accessibility -Scale issues -Varying temporal resolutions	-Strong linkage to other evidence streams -Can derive useful and meaningful 'products'	-Combine products to increase temporal depth		Anderson and Lochery, 2008; Hansen et al., 2013; Higgins, 2017; Seki et al., 2018
Documentary and historical	-Historical Cartography -landscape art -Archival	-Findability -Accessibility -Multilingual sources (German, English, Kiswahili, local) -Recording biases -Hegemonic biases	-High temporal resolution -Spatially explicit	-Dispersed archives at many levels of government and agencies	-Increase interaction with Environmental historians to improve criticality and interpretation of sources	Aleman et al., 2018; Orozco-Quintero and King, 2018
Palaeoenvironmental	-Dendrochronology -Forest histories	-Few studies -difficult to define growth ring proxy relationship	-Forest histories describe land cover changes -High spatiotemporal resolution -Spatially explicit -Works well for gallery forests and fine-scale land cover	-trees are common to many areas	-not widely used in the tropics	Krishnamurthy and Epstein, 1985; Wyant and Reid, 1992; Stahle, 2009; Maingi, 2006; Patrut et al., 2010
	-Geoarchives	-Scale issues -Spatially	-long-term environmental	-Co-located study sites with	-Multi-core, multi-site compositing	Ryner et al., 2008; Rucina et al., 2010; Öberg et al.,

Table 1 (*Continued*)

Evidence stream	Approach	Challenges	Benefits	Unexploited potentials	Solutions	Example studies
		constrained -Environmental (dis)continuity -few traditional target study site sources in arid areas -Communication between disciplines and other audiences	records -high to moderate temporal resolution	archaeology -co-generating studies with neo-ecologists and land cover modelers -new techniques specific to arid environments	-multi-scalar analyses -lots of geoarchives in arid areas remain unexplored -alternative archives (bird nests, phosphatite)	2012; Schüler et al., 2012; Finch et al., 2017; Githumbi et al., 2018b
Archaeological	-Surveying (surface finds), excavations	-Difficult to find in wet environments -Dispersed sources from private collections, national archives, peer-reviewed literature -not always spatially-explicit data -temporality varies through time with newer information -Discontinuous time series data -recent artefacts/sites often not radiometric dated -level of quantification relative to Environmental Sciences	-High number of sites -Many in arid environments	-information on human land use, social drivers and interactions	-Identifying knowledge gaps to direct research effort -Improved quantification methods	Foley, 1981; Bower and Chadderdon, 1986; van Grunderbeek, 1992; Stump, 2006; Prendergast, 2011
Anthropological, ethnographic, sociological	-Oral histories -Historical linguistics	-Difficult to establish dates with certainty -Multiple language groups	-Reconstruction of how landscapes are imagined -Learn how values have changed over time	-Continued corroboration of results with other evidence streams -Capturing and sharing of geospatial information	-more cross-disciplinary interaction -project co-design	Shetler, 2003, 2007; Orozco-Quintero and King, 2018
Syntheses and Integrated studies	-Coupled syntheses -multidisciplinary syntheses -regional studies	-Harmonising lexicons -communicating uncertainties appropriately -media miscommunication -complexities in ownership, authorship, and credit -FAIR databases, database versioning, database sharing	-Inherently multidisciplinarity -Produces state-of-knowledge reports -Reports can be translated into other languages -Reports in plain language	-Increasing and garnering momentum -co-developing cyberinfrastructure for data -Co-production with stakeholders -Online visualization tools	-co-creation of outputs scientific publications with white papers and briefings for other user groups/audiences -Identifying knowledge gaps to direct research effort	Kay and Kaplan, 2015; Hamilton et al., 2016; Aleman et al., 2018; Hughes et al., 2018; Morrison et al., 2018; Marchant et al., 2018

successful scientific endeavours and can also serve as outreach and communication toolkits (Swanson et al., 2015, 2016).

4.4. Widening perspectives and connecting science-policy

Optimising the delivery of LULCC outputs for application in policy formulation must balance the competing desires, politically-motivated reasonings and conflicts of interests that modify LULCC trajectories (Barnett et al., 2016; Tschakert et al., 2016; Fazey et al., 2018). By being inclusive of multiple scientific sources of LULCC knowledge, biases begin to be constrained, arguments are more richly nuanced, and generalizations have deeper and broader support. Syntheses and integrated landscape narratives encourage bidirectional flows of awareness, requirements, opportunities and remaining challenges, between researcher and public policy formulation communities. Improved familiarity and co-development of integrated research across the science-policy interface enables the alignment of research and increases capacity for designing policy interventions and achieving intended LULCC outcomes (Hahn, 2001). Lastly, condensing wider syntheses to generate education and outreach outputs to engage stakeholders at several levels promotes transparency, fairness and democratic processes in public policy. A lack of knowledge is not the only barrier to socio-ecological resilience in the borderlands (Reid et al., 2016). Our intention here has been to build a foundation to address the deficit in shared understanding that limits connecting knowledge and policy action. This deficit exists among researchers, stakeholders and agents of policy formulation (and political system) and requires syntheses of scientific knowledge. Steps to close these gaps include: transmission of knowledge to stakeholders, improved capacity for critical assessment of several scientific evidence sources, transparency, access to research products, well supported knowledge generalisations, and robustness assurances elevating the suite of

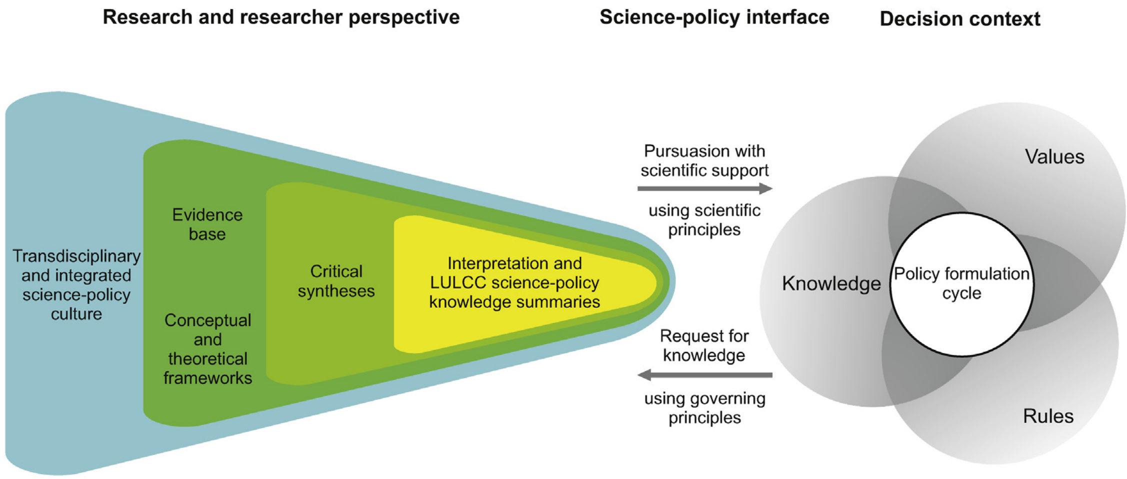

Fig. 7. A generalised knowledge map of the nested steps to integration across the land use land cover change science and land management policy interface from the perspective of the research community. This study sits between the two outer shells on the left side of the diagram (blue and green components) as part of several additional efforts that require further development to improve relationships across the knowledge and policy action gap.

scientific support to comply with evidence-based policy requirements levels (Fig. 7).

5. Conclusion

Socio-ecological systems, and the conditionalities and practices that uphold them, are compromised by knowledge and communication deficits concerning changing climate dynamics, ecosystem behaviour and societal drivers of change. The scientific community participates in efforts of outcomes-oriented research for adaptive capacity and socio-ecological transformation pathways to buffer against undesirable long-term changes (O'Brien, 2012), and approach this through multidisciplinarity, multi-stakeholder and broad audience interactions, cyberinfrastructure, and integration at the science-policy interface. Improving familiarity and mutual understanding of the knowledge sources across several LULCC disciplines and between knowledge producers and end users facilitates applying the evidence base to land management policy formulation. Knowledge summaries of human-environment interactions disseminate coherent narratives of socio-ecological change. Knowledge co-produced and used from diverse viewpoints better serve and support dialogues on equitable bioculturally-based routes to sustainable futures that accommodate customary practices, heritage and multifunctional landscapes, and provide livelihoods for people, space for wildlife, and resilience against future social environmental change (Poole, 2018; Ekblom et al., 2019). This would provide a basis for iteratively exploring informed approaches to developing scenarios of future LULCC for decision making that offer greater possibility of achieving the sought after multiple wins that enhance conservation, development and livelihoods in continuously evolving systems of human-environment interactions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work.

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