Site-specific modulators control how geophysical and socio-technical drivers shape land use and land cover

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Human utilisation of natural resources is the most important direct driver of land cover patterns in the Anthropocene. Here, we present a conceptual framework for how the effects of geophysical drivers (e.g., topography, soil, climate, and hydrology) and socio-technical drivers (e.g., technology, legal regulation, economy, and culture) on land use and land cover are shaped by site-specific modulators such as local topography and social and cultural backgrounds of individuals. The framework is demonstrated by examples from the literature, with emphasis on the north-western European lowland agricultural region. For example, a geophysical driver such as slope of the terrain constrains land use and is thereby an important driver of land covers, for example, forests. This effect of slope can vary depending on site-specific modulators such as local soil fertility, local topographic heterogeneity, and shifting human population densities. Acknowledging the importance of site-specific modulators on how geophysical and socio-technical drivers shape land use and land covers will strengthen research on human–environmental interactions – especially important with the future increase in human populations in a constant changing world.

KEYWORDS
land cover patterns, land use, non-stationarity, site-specific modulators, spatial

1 INTRODUCTION

_Homo sapiens_ is now the dominating species in the Earth System, notably by having transformed more than half of the terrestrial land surface (Ellis et al., 2010), in large part for extraction and production of resources such as food, timber, fibres, fuels, and minerals. This has resulted in massive changes of land cover patterns through, for example, agricultural expansion, livestock grazing, forestation, mining, land abandonments, and urbanisation (Ellis & Ramankutty, 2007; Sanderson et al., 2002; Vitousek et al., 1997). Thereby, human land use influences nearly all ecosystems and biogeochemical cycles (Foley et al., 2005). At the same time, the general view that the world is divided into natural biomes, based solely on biotic and abiotic factors, has been challenged; some authors have replaced these natural biomes with “anthropogenic biomes,” which are interpreted as “human systems, with natural ecosystems embedded within them” (Ellis & Ramankutty, 2007). With the predicted future increase in human populations (Steffen et al., 2007) a deeper understanding of what shapes land use and thus land cover patterns in human-dominated landscapes (Figure 1) is a central issue for geographical studies on human well-being, landscape ecology, and biodiversity conservation.

Many propositions have been put forth to describe what drives land use and thereby land cover patterns and changes, and how these act, interact, and vary in importance at various scales (Biro et al., 2013; Bürgi et al., 2004; Falcucci et al., 2007; Gao & Li,
FIGURE 1 Examples of land cover patterns in the human-dominated agricultural lowland landscapes of Denmark. (a) Landscape showing the relationship between forest and slopes of the terrain for a lowland region (picture taken near the Danish city Hobro in 2014); (b) hilly landscape with maize, grasslands grazed by cattle, and forest (picture taken near the Danish city Ry in 2012); (c, d) agricultural landscapes (pictures taken near the Danish city Aarhus in 2011); and (e) agricultural landscape with homogenous grasslands (picture taken near the Danish city Aarhus in 2014). Photographers: Mette V. Odgaard (a, b), Jens-Christian Svenning (c, d, e).
2011; Liang & Ding, 2006; Meyfroidt et al., 2013; Pineda Jaimes et al., 2010; Turner et al., 1989; Veldkamp & Lambin, 2001; Wu, 2004). Some studies have also considered how these drivers can vary in importance across regions according to geographic differences in climate and topography (de Freitas et al., 2013; Gao & Li, 2011; Kupfer & Farris, 2007; Rojas et al., 2013; Su et al., 2012; Xiao et al., 2013), but only few have analysed this issue (Gao & Li, 2011; Odgaard et al., 2014; Sandel & Svenning, 2013). For instance, steep topography can limit land use and be particularly important in landscapes characterised by relatively strong topographical heterogeneity (Acacio et al., 2010; Odgaard et al., 2014; Rouget et al., 2003; Scott et al., 2001) or in areas of high human population density (Coblentz & Keating, 2008; Sandel & Svenning, 2013). Hence, drivers of land cover patterns often vary in importance and influence at different localities depending on site-specific geophysical (e.g., topography soil, climate, and hydrology) and socio-technical (e.g., technology, legal regulation, economy, and culture) characteristics of a given area – here defined as site-specific modulators. Such spatially shifting driver–response relations are referred to as spatial non-stationarity and require particular methods for statistical analyses (Brunsdon et al., 1996). Another study has presented a conceptual framework describing only the socio-economic drivers influencing land use change (Busck & Kristensen, 2014), but not including geophysical drivers (Acacio et al., 2010; Odgaard et al., 2014; Rouget et al., 2003; Scott et al., 2001). Hence, to fully understand what drives land cover patterns in human-dominated landscapes, it is necessary to evaluate the importance of how site-specific modulators can affect the importance of geophysical and socio-technical land-use drivers.

This paper outlines how both geophysical and socio-technical drivers can shape land use and how the strength of these drivers may vary geographically according to site-specific modulators. We present a conceptual interdisciplinary framework describing drivers of land cover patterns and explicitly consider the importance of geographic variability in the effect of these potential drivers (Figure 2). The framework provides an outline for analysing and understanding land cover patterns and their dynamics, and consists of three major parts (Figure 2):

1. Geophysical and socio-technical drivers that shape land use.
2. Site-specific modulators of the effect of the drivers on land use.
3. The net effect of (1) and (2) on direct land use, and as a result, land cover patterns.

2 | A CONCEPTUAL FRAMEWORK DESCRIBING DRIVERS OF LAND USE AND LAND COVER PATTERNS

The conceptual framework depicted in Figure 2 is the basis for this paper. Combined with spatial-modelling methods and data, the intention is to use the framework as a structural approach for analysing human-induced land cover patterns in time.
and space. Appropriate drivers, as well as the analytic scale of these drivers, should be chosen based on the research question and characteristics of the research region.

The first part of the framework describes geophysical and socio-technical drivers that shape land use. Five major groups of drivers have been proposed to affect land use decisions and thereby land cover patterns: (1) technology, (2) natural conditions, (3) socio-economics, (4) public policies, and (5) cultural factors (Brandt et al., 1999). The five groups can be divided into geophysical drivers of land use (natural conditions: topography, soil, climate, and hydrology) and socio-technical drivers of land use (technology, socio-economics, public policies, and cultural factors, which is described as technology, legal regulation, economy, and culture in this framework).

The second part of the framework describes site-specific modulators of the effects of the geophysical and socio-technical drivers. That is, spatial variation in the effect of a given driver of land use can be caused by interactions with other factors, namely site-specific modulators. The geophysical and socio-technical drivers described in the first part may exhibit spatial variation in terms of how strongly they affect land use decisions due to the spatial variation of local characteristics. For example, topographic slope drives forest cover in some areas; the effect of slope might be strongest in areas characterised by large variation in elevation or low soil fertility (Odgaard et al., 2014). In this case, site-specific modulators such as variation in elevation or soil modulate the geophysical drivers that affect the resulting spatial patterns of forests differently across regions. We note that the site-specific modulators may also cause apparent spatial non-stationarity when the driver–response relation is non-linear, and the modulator affects which segment of the relation is expressed. The site-specific modulator can also be temporal variables affecting driver–response relationships at a specific site over time – temporal non-stationarity. In the framework (Figure 2), sites 1 and 2 should then refer to times 1 and 2. Moreover, the site-specific modulators will function as time-specific modulators (Figure 2). In this paper, spatial non-stationarity will have the primary focus.

The third part of the framework describes the net effect of the geophysical and socio-technical drivers and the site-specific modulators on direct land use, and as a result, land cover patterns. In areas characterised by intense agriculture, land cover patterns are closely linked to the agricultural system and to settlement activities (Brandt et al., 1999). Thus, two areas where humans clearly shape land cover patterns can be noted: (1) natural resource extraction involving the use of natural resources from the environment, such as agriculture, forestry – mainly deforestation and mining; and (2) urbanisation particularly following economic growth and population wealth (Rompré et al., 2008) and recreation such as golf courses, walking paths in public natural areas, campsites, and parks (Turner et al., 2014). As direct drivers of land cover patterns are well documented and described in scientific literature (Bürgi et al., 2004) only parts 1 and 2 of the framework will be described here. Furthermore, the framework is demonstrated with examples from the literature (Figure 3).

3 | GEOPHYSICAL AND SOCIO-TECHNICAL DRIVERS THAT SHAPE LAND USE: PART 1

As previously stated, human influence is a major driver of land cover patterns through direct land use. This land use can be shaped by geophysical drivers, such as topography, soil, climate, and hydrology, and socio-technical drivers, such as technology, legal regulation, economy, and culture (Brandt et al., 1999). In this section, we will assess how geophysical and socio-technical drivers shape land use: part 1 (Figure 2).

3.1 | Geophysical drivers shaping land use

Geophysical drivers are defined here as abiotic drivers (e.g., topography, soil, climate, and hydrology) that characterise a given area’s utility for land use. Because these drivers are difficult to separate, they will be described together in one section.

Many studies have indicated that natural vegetation tends to be situated in areas of relatively low value to humans, such as areas characterised by low soil fertility (Odgaard et al., 2013, 2014; Seabrook et al., 2007), unsuitable climate (Odgaard et al., 2011), unfavourable hydrologic properties (Biro et al., 2013; Odgaard et al., 2014; Wolfe et al., 2012), or difficult terrain (Acacio et al., 2010; Liang & Ding, 2006; Rouget et al., 2003). For example, an overlay of forest and steepness of the terrain reveal a convergence for some areas (Figure 4). Furthermore, high-elevation fields in difficult terrain located far away from roads have been abandoned more frequently, reflecting the importance of accessibility for profitable cultivation (Flinn et al., 2005; Rojas et al., 2013; Taillefumier & Piégay, 2003; Uematsu et al., 2010). Another study from Canada has shown that ecosystem services cluster together in bundles across the landscape (Raudsepp-Hearne et al., 2010). Clusters
dominated by agricultural areas were mainly situated in flat areas, and clusters dominated by natural areas were situated in areas of relative complex topography. This has also been shown for the lowland region of Denmark (Turner et al., 2014). In line with this, studies have found that topography can shape land use and thereby the distribution of forest at the global (Sandel & Svenning, 2013) and regional scales (Odgaard et al., 2014) and of other natural or semi-natural areas (Biro et al., 2013; Odgaard et al., 2013; Rouget et al., 2003) by limiting human accessibility to a given area. For example, northern European lowland forests tend to be situated in areas characterised by relatively steep slopes (Odgaard et al., 2014) (Figures 1a and 3b). The spatial distribution of set-aside fields has also been investigated for the same region (Odgaard et al., 2013), and in some areas, set-aside was found mainly in areas unsuitable for farming and characterised by steep slopes, high wetness, and low soil fertility. Hence, there was a clear link between the geophysical conditions and the decision on where to set aside (Odgaard et al., 2013). A similar effect has also been shown for a number of other countries. In Italy, agricultural land covers are mainly situated on flat areas whereas natural areas are found in mountainous areas (Falcucci et
al., 2007); and in Hungary, grasslands were less prone to conversion to agriculture when located in wet areas unsuitable for cultivation (Biro et al., 2013). Hence, the geophysical drivers of difficult topography, high wetness, and low soil fertility function as constraints and shape land use in regions characterised by relatively low topographic heterogeneity (Odgaard et al., 2014) and those characterised by high topographic heterogeneity (Kobayashi & Koike, 2010).

Climate can also drive land use by acting as a land use constraint. This is most distinct in regions with extreme weather conditions where human land use is almost non-existent, such as the Arctic, the Antarctic, and large deserts (Ellis & Ramankutty, 2007), but is also visible in areas of higher land use potential. At the global scale, climate constrains crop distributions which depend on certain growing conditions, as is the case for the distribution of C4 cultivated crops (Odgaard et al., 2011; Olesen & Bindi, 2002; Olesen et al., 2007). Climate can also act as a small-scale constraint, such as the case of a European temperate region where climate shapes human decisions on whether to grow crops adapted to warm climates.
In one such region, Denmark, the spatio-temporal dynamics of maize distribution have been investigated (Odgaard et al., 2011). Denmark, together with northern Germany and England, marks the northward-moving limit of maize cultivation in Europe (Olesen et al., 2007), and thus, this country is of particular interest to the discussion on climatic constraints. In this region, the area cultivated with maize has increased over a decade, partly due to temperature increases (i.e., a decrease in the climatic constraint) (Figure 5).

3.2 | Socio-technical drivers shaping land use

Socio-technical drivers are here defined as drivers that can influence human decisions on whether to access a given area (e.g., technology, legal regulation, economy, and culture) (Brandt et al., 1999).

3.2.1 | Technology

Traditional farming methods have created heterogeneous landscapes composed of patches of agricultural land in rotation, grazing, grasslands and more natural or semi-natural areas arranged in a mosaic-like structure (Odgaard & Nielsen, 2009). These structures are particularly prevalent in developing countries (Gliessman, 2006), although traditional farming methods have now largely been replaced by more effective technologies (e.g., the use of artificial fertilisers and pesticides, gene technologies, mechanised farming, roads, and efficient transportation systems), particularly in areas experiencing population and economic growth (Biro et al., 2013; Lepers et al., 2005). In developed countries existing technologies facilitate high production and an increase in field size (White & Roy, 2015) and a homogenising tendency of the landscape, for example, maize fields in the US corn belt (Leff et al., 2004), cereal fields in the European lowland (Odgaard & Nielsen, 2009), and economic-optimisation-founded aggregation of small farms into larger, more profitable farms (Uthes et al., 2011), but also

**FIGURE 5** Example of temperature as a driver of land use in Denmark: (a) spatial maize area for the year 1999, (b) spatial maize area for the year 2008; and (c) illustration of temperature and maize area increase for the years 1999–2008 (Odgaard et al., 2011).
land abandonments in areas with less sophisticated transportation systems (Biro et al., 2013; Flinn et al., 2005; Uematsu et al., 2010).

### 3.2.2 Legal regulation and economy

Legal regulation is a particularly powerful driver that acts on both coarse (European Commission, 2011) and fine scales (Kristensen et al., 2009; Odgaard et al., 2011). One strong regulative force includes agricultural subsidies, which can change the rural landscape dramatically over short periods of time (Henle et al., 2008; Odgaard et al., 2013).

For example, in the mid-1990s in Denmark, economic support for maize cultivation and other whole-crop silage cereals was granted, but with no subsidies for fodder beets (Rodgers, 2003). This, together with changes in global demand and market conditions in combination with rising temperatures favouring maize (which undergoes C4 photosynthesis), altered the rural European landscape (Odgaard et al., 2013; Olesen & Bindi, 2002) by, for instance, increasing the abundance of maize fields in Denmark (Odgaard et al., 2011). Another example is from central sub-tropical China, where economic support for oranges has increased pressure on agricultural fields and degraded cultivated terraces close to human settlements and main roads for ease of fruit distribution (Schönbrodt-Stitt et al., 2013). Agricultural and agro-environmental subsidy schemes and changes in legal regulations can also cause changes in the abundance of natural land cover objects, such as water elements (Kristensen et al., 2001), pastures (Kristensen et al., 2004), forest patches (Kristensen et al., 2004), and set-aside fields (Primdahl et al., 2003). For example, set-aside field abundance in the landscape tends to follow legal regulations set by the EU. These regulations include rules on whether a farmer should set aside fields and is driven by grain stocks and prices, and the effects are quickly seen in the amount of set-aside occupying the landscape (Odgaard et al., 2013). This human response – visible in the landscape – to changes in legal regulations or subsidies can also have a displacing effect. As environmental regulations strengthen in one area, farmers can, in some regions, move their practice to another area with less regulative constraints, thereby causing unintentional land cover patterning in less-restrictive areas (Henle et al., 2008). Although such displacing effects can also originate from urban areas that do not significantly affect land cover per se, the socio-technical linkages with the surrounding rural areas can cause extreme changes in land cover patterns because the inhabitants depend on ecosystem services from the surrounding area (Lambin et al., 2001). In light of the expected future increase in demands for land for various purposes (Steffen et al., 2007), it is plausible that when an area is cultivated, its original purpose is replaced and moved to other areas, thereby causing a general cascade effect (Searchinger et al., 2008). This also raises questions on the actual environmental benefit of biofuels, as their growth depends on the continuous acquisition of land (Searchinger et al., 2008).

### 3.2.3 Culture

Cultural backgrounds, human aesthetics, and amenity values can also determine land use decisions. Many studies indicate that landowners’ perceptions of landscapes can influence their land use decisions (Busck, 2002; Herzon & Mikk, 2007; Kristensen et al., 2001; Odgaard et al., 2013; Wilson & Hart, 2001). Individually, decisions can be guided by neighbour influences (Cook & Lee, 2011; Hersperger & Bürgi, 2009; Nassauer, 1995), emotions, and aesthetics (Odgaard et al., 2013). For example, some farmers decide to implement environmentally friendly actions on their land to enhance their own experience of the surroundings and improve wildlife levels on their property (Busck, 2002). Others consider nature values when making set-aside management decisions by acknowledging the potential nature value of such areas (Bracken & Bolger, 2006; Kristensen et al., 2001; Odgaard et al., 2013). Of course, other farmers value short-term economic benefits more than the aesthetic and nature value of the land (Rounsevell et al., 2003). Thus, land cover patterns depend largely on local land owners’ “state of mind” (Odgaard et al., 2013). Cultural variables can be measured and have a spatial relation by, for example, interpreting questionnaires with spatial information on each respondent. Another way is to use, for instance, recreational areas or nature areas within a research unit as a proxy for human aesthetics. Hence, depending on available data, the variables should be tailored to fit the research question.

### 4 SITE-SPECIFIC MODULATORS OF THE GEOPHYSICAL AND SOCIO-TECHNICAL DRIVERS: PART 2

Geophysical and socio-technical drivers limiting land use may exhibit spatial variation in how strongly they affect land use decisions. In this section we will assess the site-specific modulators of the effects of the drivers on land use: part 2 (Figure 2).
4.1 | Acknowledging the effect of site-specific modulators

A spatial varying relationship between driver and response is defined as spatial non-stationarity and can result from site-specific modulators of the effect of the drivers (Gao & Li, 2011; Martín-Queller et al., 2011; Odgaard et al., 2013), notably, interactions among drivers, non-linear effects of drivers, as well as spatial variation in drivers. In previous papers, this non-stationarity has been assessed using statistical methods such as geographical weighted regression (GWR) (Kupfer & Farris, 2007; Rojas et al., 2013; Su et al., 2012; Xiao et al., 2013). GWR is a statistical method that describes a possible spatially varying relationship between driver and response variables (Fotheringham et al., 2001). The method produces a number of local models, each with individual parameter estimates and detects the spatial non-stationarity between driver and response but not the cause of this relationship – site-specific modulators. Previous papers have described these relationships through a discussion of what could drive the spatial differences in driver and response relationships. For example, one study from China has detected spatial differences in how well specific drivers explain landscape fragmentation (Gao & Li, 2011). The authors explain these relationships in their results with a simple overlay of land cover types and conclude that fragmentation can be explained by distance to roads in highly urbanised areas and to a lesser extent in less urbanised areas. Another study from Mexico detected spatial differences in the importance of drivers that explain forest loss across their study area (Pineda Jaimes et al., 2010). They discussed spatial differences in technology levels and subsidy implementation in their region as plausible reasons for the detected spatial pattern. Furthermore, Odgaard et al. (2011) described how the importance of livestock densities and sandy soils on maize distributions changed depending on site-specific temperature change over a decade. In this example, maize distribution and sand percentage in the soil exhibited a strong spatial coupling at the beginning of the study period (characterised by relatively cold temperatures). Sandy soils have a higher heating rate compared with more loamy soils. Hence, during cool periods, maize will produce the highest yields in sandy soils. At the end of the study period (characterised by relatively warm temperatures), the strong coupling of sandy soils and maize yields decreased and was replaced with a stronger coupling of maize with ruminant livestock (Figure 6), which is widely fed with silage maize in Denmark. Hence, local socio-technical drivers, such as the need for fodder in certain regions (described by livestock densities) and geophysical drivers (such as sandy soils), compete as an incentive to grow maize and vary in importance depending on regional geophysical constraint or release (such as temperature) (Figure 5). In this study, the modulator is the temperature, which is changing over time for one specific site. In this case, the time-specific modulator affects driver–response relationships at two different times, referred to as temporal non-stationarity (Figure 3b).

Non-stationarity can also be described by conducting similar analysis in two areas delimited by site-specific modulators, such as climate, topography, human influence etc. One such study from South America modelled the effect of human and environmental variables on ecosystem functional diversity in three different areas separated by level of human influence (Alcaraz-Segura et al., 2013). In this study the ecosystem functional diversity went from being described by mainly environmental variables to land use variables with increasing human influence.

Economic and cultural differences between regions as well as economic status, social and cultural backgrounds of individuals can also affect how humans respond to various geophysical and socio-technical drivers. For example, similar
geophysical properties in two different regions might not result in the same land use, simply due to different cultural traditions in the two locations. Also, ecosystem restoration can be difficult in developing countries due to a lack of nature monitoring (Fasona & Omojola, 2009). This might not be an issue in developed countries, where nature surveillance is allocated more resources due to an economic surplus (Wenhua, 2004). Hence, land use priorities depend on the economic status of a region because human vital needs are often the highest priority. However, some large nature reserves rely on economic input from global sources and are therefore not dependent on regional economies (James et al., 2001).

### 4.2 Analysing the effect of site-specific modulators

A few studies have extended the descriptive method of non-stationarity by using spatial modelling methods to describe the underlying effects of spatially varying relationships (Alcaraz-Segura et al., 2013; Moeslund, Arge, Bocher, Dalgaard, Ejrnæs et al., 2013; Moeslund, Arge, Bocher, Dalgaard, Odgaard et al., 2013; Odgaard et al., 2013; Sandel & Svenning, 2013). For example, Odgaard et al. (2014) used GWR (Fotheringham et al., 2001) to consider spatially varying associations between forested areas and topography (Odgaard et al., 2014). The degree to which topography could explain forest location – that is the coefficient of determination, \( R^2 \) – was used as a response variable, which is interpreted as a value of how well topography can explain forest distribution. Topographic variables were particularly important in describing forest distributions in areas characterised by heterogeneous terrain (Figure 4b). As suggested in other studies, this could reflect a tendency for humans to leave forested areas on relatively steep slopes in regions that are not easy accessible (Rouget et al., 2003; Scott et al., 2001). Furthermore, the forest–topography relationship tended to be significant in areas with low soil fertility, which again reflects the human utilisation of areas with high agricultural potential. From a global perspective, human population densities have been shown to be an important determinant of how well topography can explain forest occurrence (Sandel & Svenning, 2013). In this cross-scale global study, forest was well explained by topography in areas with high human populations and poorly explained in areas with a low human impact. This suggests that at the global scale, human land use is constrained by topographic accessibility even – and, in fact, especially – where human population pressure is high (Figure 3a). Another study further indicates a stronger linkage between ecosystem diversity and relief heterogeneity in human-influenced areas compared with natural areas (Alcaraz-Segura et al., 2013). However, some highly populated areas such as the surroundings of the Panama Canal have high concentrations of agricultural areas toward zones of high elevation with complex topographies rather than natural areas (Rompré et al., 2008). This was also the case for highly populated areas in South America where the positive effects of land use on natural area diversity decreased in areas with extreme human pressures (Alcaraz-Segura et al., 2013). This could indicate a need to cultivate the land despite topographic obstacles (topographic variability of 500 m for the Panama region). The link between topography and forest is also weak in Denmark in areas of high soil fertility, that is, in areas of high agricultural value (Odgaard et al., 2014). Hence, in some human-dominated agricultural regions, much of the natural habitat will be converted to agriculture, as has been the case for central Panama (Rompré et al., 2008) and China (Schönbrodt-Stitt et al., 2013), even on steep slopes. This will result in a landscape characterised by urban areas on the flat terrain, agriculture on the steep slopes, and forest pushed towards the edges of the area (Rompré et al., 2008).

### 4.3 Importance of site-specific modulators

If the spatial non-stationarity in the effect of geophysical and socio-technical drivers constraining or facilitating land use is not acknowledged in research, landscape management and conservation outcomes might become suboptimal. For example, although China has previously invested a large amount of money into the restoration of Chinese forests (Wenhua, 2004), the utility of the project has been questioned (Cao et al., 2011). Cao et al. (2011) highlight the problematic aspect of large-scale management plans. Chinese regions display different geophysical properties, which can cause problems if all regions are subject to similar management. An attempt to increase forested area and decrease soil erosion has failed in some arid and semi-arid regions to some extent. These areas naturally support low and dense shrub vegetation, which lowers wind speed near the soil surface, and thereby also soil erosion, which is also the typical used vegetation in restoration projects implemented to decrease soil erosion (Zhou et al., 2016). An increase in more open and young forest will cause an increased wind speed near the soil surface and thereby a higher soil erosion rather than lowering it, which is the intention. Furthermore, newly planted trees tend to deplete the already dry soil of available water, thereby decreasing the likelihood of new understory vegetation growth in such areas. This example clearly demonstrates non-stationarity in how socio-technical drivers (in this case, large-scale management planning) affect land use depending on site-specific geophysical drivers (in this case climate and soil). Also Chinese ecological restoration projects show spatial variation in effectiveness depending on site-specific modulators such as roughness of the terrain and local rainfall, despite overall high human investments (Tong et al., 2017). Still, other findings indicate positive
effects of Chinese restoration projects on, for example, carbon sequestration (Lu et al., 2018) and forest recovery (Viña et al., 2016). Hence, management plans must be designed to fit the geophysical characteristics of target regions.

5 | CONCLUSIONS

To investigate drivers of land cover patterns, it is crucial to base analyses on high-quality geographic data and to use spatially explicit modelling that properly accounts for spatial complexities. We have presented a conceptual framework for understanding the drivers of land use and thereby land cover patterns. The framework considers spatially shifting driver–response relations – referred to as spatial non-stationarity – as well as the causes of this non-stationarity, notably interactions among drivers, non-linear effects of drivers, and spatial variation in drivers. The framework presented provides an outline with room for plasticity to fit a certain area or scale, and despite its shortcomings, we believe that it can be a useful starting point in future research on how humans respond to their surroundings and for developing the spatial overview needed for better resource management.

In summary, although socio-technical drivers are an important factor driving land cover patterns, geophysical drivers are also of strong importance. The relative roles of these two drivers shift in importance across space depending on local conditions. For example, economic considerations at the farm level might lead to a preference for crops that attract economic subsidies compared with crops that do not. However, if the climate is unsuitable for a specific crop, it is less likely to be grown despite subsidies. Similarly, if an area of high agricultural value (high soil fertility) is difficult to access, it is less likely to be cultivated than an easily accessible area. In these two specific examples, the framework is verbalised as follows (Figure 2): Economy/soil is an important driver of direct land use (part 1). The effect of economy/soil on land use can display non-stationarity explained by site-specific characteristics such as climate/topographic slope (part 2). These combined effects shape direct land use and result in actual land cover patterns (part 3).

We recommend including these spatially varying interactions of geophysical and socio-technical drivers and their effects on how humans decide to use land in spatial statistical modelling of future land cover patterns and change (e.g., use the driver–response relationship [coefficient of determination, \( R^2 \)] as the response variable and relevant geophysical and socio-technical drivers as explanatory variables). This will strengthen spatial modelling approaches used to refine a firmer understanding of what drives land use and land cover patterns.

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