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Identifying drivers of land degradation in Xilingol, China, between 1975 and 2015

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ABSTRACT

Land degradation occurs in all kinds of landscapes over the world, but the drivers of land degradation vary from region to region. Identifying these drivers at the appropriate spatial scale is an essential prerequisite for developing and implementing appropriate area-specific policies. In this study, we investigate nine different driving factors in three categories: human disturbance, water condition, and urbanisation. Using partial order theory and the Hasse diagram technique, we analyse the temporal and spatial dynamics of these drivers and identify the major drivers of land degradation at the county level in the Xilingol League, China. Our findings indicate that: (i) in eight out of the region's 12 counties, human disturbance was the dominant driver responsible for land degradation up to 2000, followed by water conditions, while urbanisation was the dominant driver in only four counties; (ii) the effects resulting from human disturbance and water availability decreased after 2000, while urbanisation became the dominant driver for land degradation in seven counties. The influence of human disturbance in this region has decreased, which suggests that ecological protection policies that were designed to control population and livestock numbers have worked as intended for this region. However, land degradation has continued and new policy measures are required to ease the effect of urbanisation.

1. Introduction

Land degradation (LD) is a global problem that is closely connected with threats to food and energy security, a decline in standards of living, and the loss of biodiversity (Reed et al., 2011). The phenomenon has been defined as any loss of soil quality, productivity, biodiversity, standards of living, or the provision of other ecosystem goods and services, ranging from slight decline to complete destruction or transition into different land uses (Lambin et al., 2003). Most severe cases are associated with arid, semi-arid and dry sub-humid zones, which together cover about 47% of the earth's terrestrial surface (Gisladottir and Stocking, 2005). Closely interwoven with climate change, LD has given rise to a multitude of national and international policy responses.

Understanding the drivers of LD is crucial for the development of policies and measures that aim to turn current trends towards more socially and environmentally friendly outcomes. The drivers of LD are numerous and complex, and they vary across regions. Climate change, economic and technological development, cultural habits and political contexts have all been identified as important drivers in LD processes (Kirui, 2016; Reed et al., 2011). However, data on drivers concerning land use changes are scarce, which is why most of the recent analyses look at these drivers as if they were static (Deng et al., 2011; Gollnow et al., 2018). In light of the idea that LD is a dynamic process (Batunacun et al., 2018), the drivers themselves should also be considered according to their temporal and spatial dynamics.

Due to its fragile grassland ecosystems, the arid to semi-arid area of the Xilingol League, located in Inner Mongolia, China, makes an excellent case study for researching LD. Furthermore, Xilingol has been subject to the entire range of China's grassland policies. Climate and human disturbance have been found to be the major driving forces for grassland degradation in this area (Hu et al., 2015; Sun et al., 2017); urban as well as rural development came at the expense of much of the grassland in this area, especially after 2000 (Batunacun et al., 2018). Road construction and mining development not only destroyed grassland, but also fragmented the remaining grassland area and consumed significant amounts of groundwater resources (Deng et al., 2011; Tao et al., 2015). In our present study, we collected nine potential drivers of land use changes, and analysed data from 1975, 2000 and 2015, to

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unveil the relationship between these drivers and LD. The nine drivers include the human population density, livestock density, the presence of urban structures, activities by rural settlers, road construction, mining, the presence of water bodies and two climate factors (temperature and precipitation).

In a bid to explore the drivers' relation to LD, numerous methodologies have been used in previous studies. For example, statistical models (e.g. logistic regression, principal component analysis) have been employed to unveil the statistical relationships between various drivers and grassland degradation (Gao et al., 2015; Lin et al., 2014). Scenario analysis using land use models (e.g. the CLUE-S model, see Verburg et al., 2002) were based on socioeconomic or biophysical drivers (Li et al., 2012), while factors associated with deforestation and degradation have been identified using machine-learning algorithms (Dlamini, 2016). Geist and Lambin (2002) and Kirui (2016) have summarised possible drivers of LD in literature reviews. A rich body of studies also exists that has investigated the relationship between drivers and LD, both quantitatively and qualitatively. However, the same causal drivers can lead to diverging consequences in different contexts because of their varying interactions with other proximate and underlying causes of LD (Kirui, 2016). For this reason, it is necessary to use all available driver information separately, instead of merging them into one composite indicator, and to rank and compare LD drivers to provide decision-makers with effective information to derive adjustments to current ecological policies. The concept of Partial Order Ranking (POR) has been identified as one tool that can fill this gap; POR has been shown to be useful in environmental science when sets of qualitative indicators need to be compared and evaluated (El-Basil, 2006). Moreover, the Hasse Diagram Technique (HDT) helps to diagram partial order relations of all objects in such a set (Wieland and Bruggemann, 2013).

The partial order theory has been used in many studies, e.g. in risk assessments of chemicals (Bruggemann and Voigt, 2012), ecosystem service comparisons (Tsonkova et al., 2015) and water quality assessments (Simon et al., 2006). In this study, we utilise POR as a useful tool to analyse drivers of LD with the aim of adjusting land use management strategies at the county level. The objective of this study is therefore to use POR to (1) analyse temporal and spatial LD driver dynamics in Xilingol; (2) compare and rank the LD drivers at the county level; and (3) summarise the ecological policies and measures that were initiated in Xilingol between 1980 and 2020 as well as to discuss possible policy measures for the future.

2. Data and methods

2.1. Study area

The Xilingol League is located in the centre of Inner Mongolia, spanning from 41.4 °N to 46.6 °N and from 111.1 °E to 119.7 °E (Fig. 1) and covering an area of 206,000 km^2. The mean annual temperature in Xilingol (1958–2015) was 2.2 °C and the mean annual precipitation was 278 mm. Its population has grown to 1.044 million people as of 2015, of which around 37% live in the rural parts of the league. About 87% of the land is covered with grassland, which is subject to livestock grazing. Animal husbandry had long been the major industry, and is still significant; livestock has principally consisted of sheep, goats and cattle, which produce dairy products and wool, especially cashmere. Xilingol is also rich in mineral resources, such as coal, oil, copper, gold, and many other nonferrous metals. Since 2008, the mining industry has emerged as the dominant economic sector, making animal husbandry the second-most important source of income (Yang et al., 2011). Xilingol has fertile grassland in northern China, but sandstorms have increased in recent decades (Gou et al., 2010). In light of this, a combination of different ecological policies has been launched to combat ecological issues.

There are a total of twelve counties in Xilingol: two municipalities (XL: Xilinhot, EL: Erlianhot), nine banners (an administrative unit equivalent to a county, DW: Dongwuzhumuqin, XW: Xiwuzhumuqin, AB: Abaga, SZ: Sunitezuo, SY: Suniteyou, XH: Xianghuang, ZXB: Zhengxiangbai, ZL: Zhenglan, TP: Taipusi) and one county (DL: Duolun; Fig. 1). The county/banner is the third level in China's administrative hierarchy, below provinces and prefectures. Since the counties possess their own administrative government, we choose the county (or banner or municipality) as our unit of analysis, given that we seek to target county governments with our suggestions for creating or improving their regional land use plans (Deng et al., 2008).

2.2. Land degradation data and processing

This study defines LD based on land use conversion, such as the loss of grassland, water bodies and woodland due to transformation into cropland, land development, and unused land (land that is not put into practical use or that is difficult to use), while grassland degradation is referred to as a decline in grassland coverage (Batunacun et al., 2018). We analysed LD based on a land use and land cover change (LUCC) analysis in a previous study (Batunacun et al., 2018). The results indicate that two distinct phases emerge: during Phase 1 (1975–2000), 11.4% (22,937 km^2) of the total area degraded, of which grassland degradation accounted for 8.2%. During Phase 2 (2000–2015), a further 9.5% (19,124 km^2) degraded, including 7.5% for grassland degradation. However, the comparison of the two periods revealed that the degradation rate has further increased (from 0.46% of total area annually to 0.64%; Batunacun et al., 2018), and that LD continues to be the main ecological issue in Xilingol (Batunacun et al., 2018). In order to assess which drivers were probably responsible for the LUCC observed, we processed all LD data in a 1×1 km^2 grid using ArcGIS, creating a total of 22,579 pixels in Phase 1 and 19,140 pixels in Phase 2 (Fig. 2).

2.3. Identifying possible drivers

This study began by compiling a list of possible drivers of land degradation (Geist and Lambin, 2002; Mirzabaev et al., 2016) and grassland degradation (Li et al., 2012) from previous literature. Nine independent variables were created to account for drivers of land degradation: the distance to the nearest urban centre (hereafter referred to as "urban"), the distance to the nearest rural settlement ("rural"), the distance to the nearest road ("roads"), the distance to the nearest mining area ("mining"), the distance to the nearest surface water body ("water bodies"), the human population density ("population"), the livestock density ("livestock"), the mean growing season temperature ("temperature") and the annual sum of precipitation ("precipitation"). In an attempt to ensure consistency with the LD process, we collected all variables at three distinct points in time: 1975, 2000 and 2015 (livestock data were not available for 1975, so we used livestock data from 1978 in this study; Table 1). Climate factors were extracted from the longest available weather data set and, to reflect the fact that grassland is more sensitive to the growing season (April to Sep), we used the average growing season temperature (1958–2015; Table 1). We grouped all variables into three categories: "human disturbance", represented by population and by livestock density; "water conditions", represented by the distance to the nearest water body, by temperature (as a proxy for evapotranspiration) and by precipitation; and "urbanisation/industrialisation", which includes distances to urban centres and rural settlements, to roads, and to mines (from here on, we refer to this group as "urbanisation" for the sake of simplicity). A study by Li et al. (2012a) previously identified increases in human population and in the number of livestock as the major driver of grassland degradation in Xilingol. Surface water bodies, precipitation and temperature have an important effect on soil moisture, and vegetation in the arid and semi-arid area of Xilingol responds very sensitively to changes in water conditions, especially to the drying out of surface waters (Fan et al.,

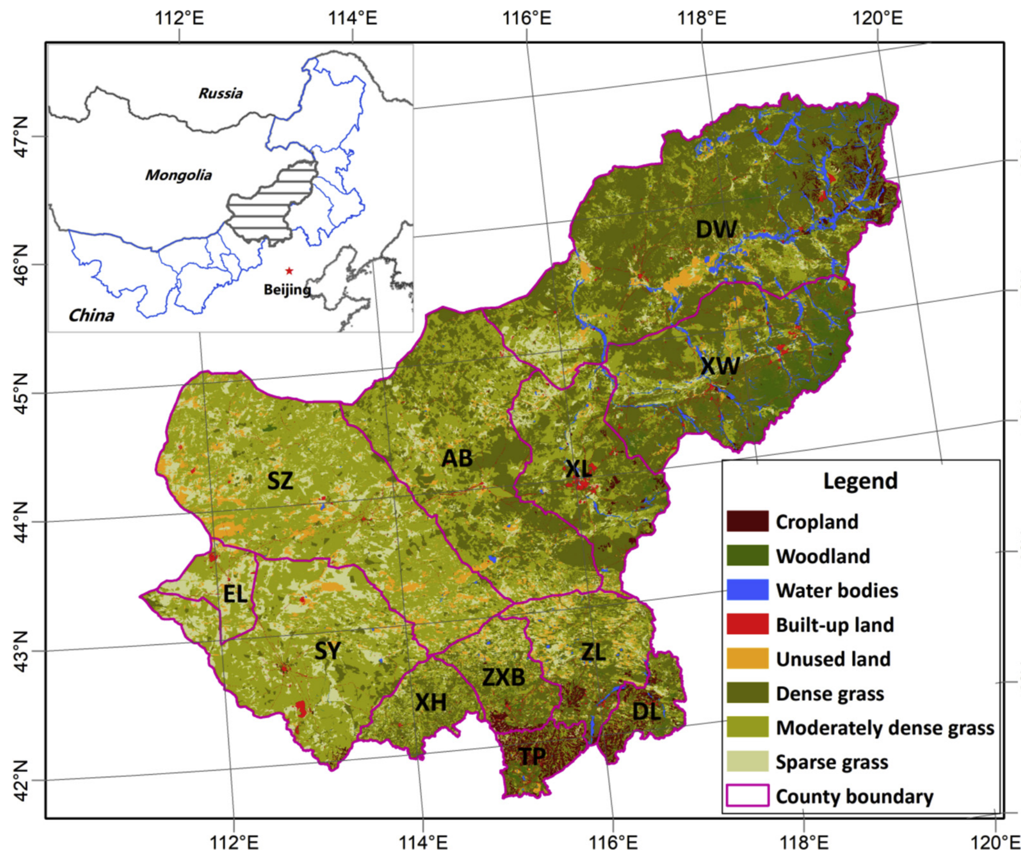


Fig. 1. Land use / land cover (2015) in Xilingol.
Note: DW, Dongwuzhumuqin; XW, Xiwuzhumuqin; XL, Xilinhot; AB, Abaga; SZ, Sunitezuo; SY, Suniteyou; EL, Erlianhot; XH, Xianghuang; ZXB, Zhengxiangbai; ZL, Zhenglan; DL, Duolun; TP, Taipusi.

2010; Tao et al., 2015). Furthermore, urbanisation, road construction, and the establishment and development of mines have consumed much of the grassland area, leading to grassland area fragmentation and degradation (Chen et al., 2017; Qian et al., 2014; Tao et al., 2015).

We used different measures to quantify these drivers (D). Based on the 1 × 1 km^2 grid cell for both phases of LD, we defined the following drivers using the following methods: (1) We used ArcGIS to determine the Euclidean distance (Lin et al., 2014) from an LD pixel to corresponding water bodies, urban areas, rural settlements, roads and mines. (2) We processed the human population data into density data for the three time points (1975, 2000, 2015, see Table 1), and we converted all livestock into sheep units (Akram et al., 2009; Xie and Sha, 2012) for every grassland pixel for the three points in time. (3) For daily temperature and precipitation data, in combination with elevation data, we

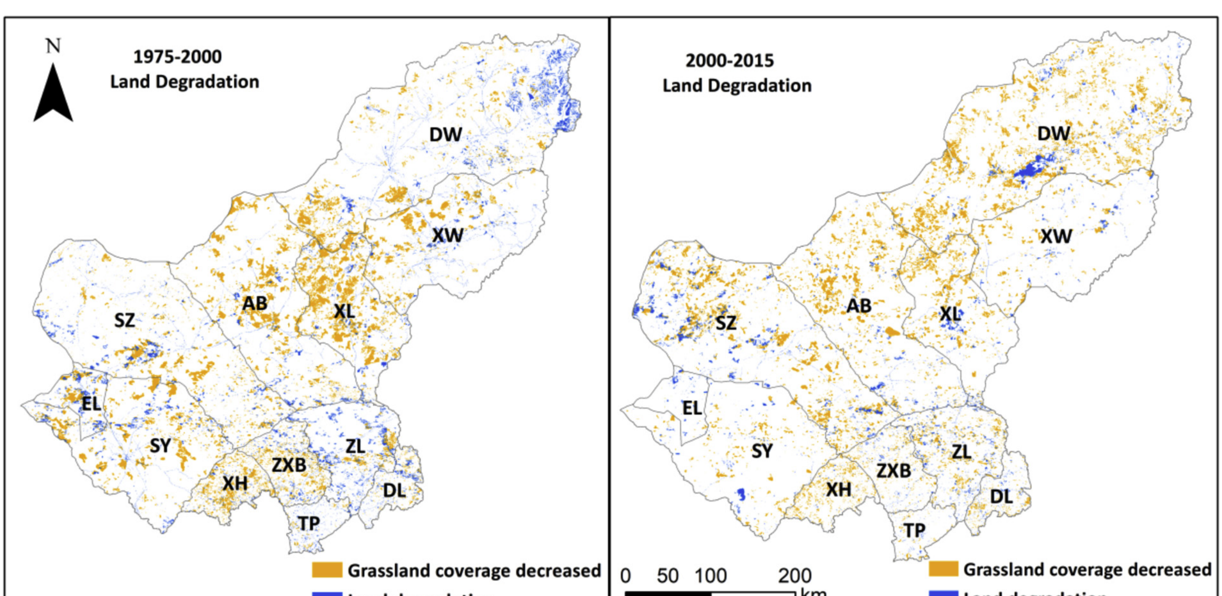


Fig. 2. Land degradation in two phases: 1975–2000 (left) and 2000–2015 (right).

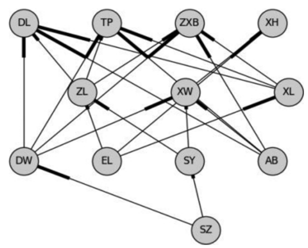
Table 1
Driver definitions and derivations.

Driver processes and orientation									
Categories of all drivers	Urbanisation/industrialisation				Water conditions			Human disturbance	
Driver name	Urban	Rural	Road	Mining	Water body	Temperature	Precipitation	Population	Livestock
Time series	1975/1978, 2000, 2015				1975, 2000, 2015	Daily data from 1958 to 2015		1978, 2000, 2015	
Data sources	Remote sensing images (Landsat MSS/TM/ETM*)					China Meteorological Bureau		Inner Mongolia Statistical Yearbook	
Measures	Distance measures				Distance measures	Average temperature from April to September	Annual precipitation	Population density	Sheep unit density only for grassland
Driver abbreviations	Distance to urban: Durban1975, Durban2000, Durban2015 Same as distance to rural, road, mining				Distance to water body: Dwater1975 Dwater2000 Dwater2015	T1958-2000 T2000-2015	P1958-2000 P2000-2015	1975popD 2000popD 2015popD	1978sheepD 2000sheepD 2015sheepD
Description	The Euclidean distance from the land degradation object to the driver object				The Euclidean distance from the land degradation object to the closest water body	Kriging to produce a temperature and precipitation value for every land degradation object		Calculation of population and sheep unit density for every land degradation object.	
Unit	km				km	°C	mm	person/km^2	sheep unit/km^2
Normalised process	Normalising drivers to [0,1]								
Orientation (the definition is stated below)	The closer to urban or rural centres, roads or mines, the higher the pressure for grassland overuse or use change is. From the smallest to the largest value, the corresponding normalised value is [1, 0]				The further away from surface waters, the more easily degrading occurs. From the smallest to the largest value, the corresponding normalised value is [0, 1].	With higher temperatures, more soil water is lost through evaporation. From the smallest to the largest value, the corresponding normalised value is [0, 1].	With lower precipitation, less water is available to sustain grass growth. From the smallest to the largest value, the corresponding normalised value is [1, 0].	The higher the density of inhabitants or livestock, the more intense land use is. From the smallest to the largest value, the corresponding normalised value is [0, 1].	

*MSS: Multi Spectral Scanner (Landsat 1–7), TM: Thematic Mapper (Landsat 4, 5), ETM: Enhanced Thematic Mapper (Landsat 7).

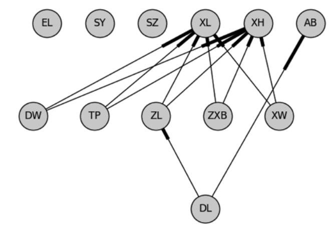
Table 2
Hasse diagrams and their input data for all indicator groups from 1975 to 2000.

(a) Human disturbance



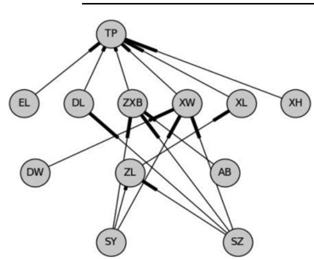
County	Population density 1975	Population density 2000	Sheep unit density 1978	Sheep unit density 2000
DW	0.01	0.02	0.12	0.40
EL	0.02	0.05	0.00	0.00
DL	0.38	0.44	0.73	0.79
TP	1.00	1.00	1.00	0.53
ZL	0.11	0.11	0.73	0.38
ZXB	0.18	0.18	0.75	0.85
SY	0.03	0.04	0.12	0.24
SZ	0.00	0.00	0.12	0.15
XW	0.04	0.04	0.18	0.87
XL	0.10	0.14	0.01	0.46
XH	0.08	0.08	0.42	1.00
AB	0.01	0.01	0.09	0.44

(b) Water conditions



County	Distance to water 2000	Distance to water 1975	Precipitation 1958–2000	Temperature 1958–2000
DW	0.14	0.28	0.00	0.58
EL	1.00	1.00	1.00	0.00
DL	0.10	0.19	0.59	0.33
TP	0.03	0.01	0.01	0.57
ZL	0.12	0.22	0.81	0.38
ZXB	0.11	0.12	0.55	0.52
SY	0.59	0.64	0.54	0.28
SZ	0.30	0.39	0.83	0.08
XW	0.00	0.00	0.17	0.76
XL	0.44	0.36	0.81	1.00
XH	0.18	0.49	0.89	0.79
AB	0.35	0.37	0.73	0.34

(c) Urbanisation/industrialisation



County	Distance to urban land 1975	Distance to rural settlements 1975	Distance to road 1975	Distance to mine 1975	Distance to urban land 2000	Distance to rural settlements 2000	Distance to road 2000	Distance to mine 2000
DW	0.00	0.54	0.29	0.23	0.11	0.60	0.75	0.79
EL	0.77	0.02	0.00	0.79	0.71	0.00	0.62	0.78
DL	0.96	0.61	0.61	0.60	0.94	0.56	0.17	0.43
TP	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
ZL	0.49	0.29	0.78	0.70	0.32	0.20	0.40	0.77
ZXB	0.78	0.54	0.69	0.68	0.71	0.49	0.79	0.68
SY	0.47	0.00	0.41	0.28	0.29	0.00	0.14	0.55
SZ	0.25	0.18	0.25	0.09	0.00	0.07	0.00	0.16
XW	0.50	0.67	0.64	0.61	0.34	0.64	0.82	0.85
XL	0.58	0.34	0.91	0.88	0.72	0.34	0.80	0.82

(continued on next page)

used a Kriging interpolation algorithm (Nalder and Wein, 1998) to produce the 1 × 1 km^2 raster data via Python, and then extracted all grid cells with LD attributes.

2.4. Partial order ranking and the Hasse diagram technique

2.4.1. Partial order ranking theory

Partial order theory allows researchers to conceptualise comparison of elements, especially if they possess more than one indicator. Partial ordering also enables all information about the objects to be maintained (Brüggemann and Carlsen, 2006). In the present study, POR has been used to rank the drivers of land degradation in Xilingol, followed by a comparison of the ranking results for the two periods (P1: 1975–2000, P2: 2000–2015).

Given a set of objects, X = {a, b, c…}, objects a, b, c, etc., are compared with each other. Therefore, in this study, X refers to counties, and a, b, c denotes the individual county or banner. For a partial order, the following axioms are valid (Hilckmann et al., 2017).

(1) (Reflexivity): a ≤ a, for all a ∈ X;
(2) (Transitivity): If a ≤ b and b ≤ c, then a ≤ c, for all a, b, c ∈ X;
(3) (Antisymmetry): If a ≤ b and b ≤ a, then a = b, for all a, b ∈ X.

In the study presented here, elements and objects both refer to counties. Here, the "element" refers to the theoretical concept, whereas "objects" are used as the generalisation for the counties/banners of Xilingol.

2.4.2. The Hasse Diagram Technique (HDT)

A Hasse diagram is a visual representation of partial order relations among objects described by a number of indicators; let X be the finite set of objects and IB the set of indicators q_i, (i = 1,…,|IB|). The objects and their indicators are called "partially ordered sets" (posets). Posets can be described as a data matrix Q (N × R) containing N objects and R variables or indicators (Voyslavov et al., 2013). In this study, objects have been described as land degradation in twelve counties in two phases (P1 and P2); these objects were denoted as Counties_P1 and Counties_P2, and a total of nine indicators were grouped into three categories (see Table 2). The three categories with their three points in time were denoted as IB_human_P1, IB_water_P1, IB_urban_P1, and IB_human_P2, IB_water_P2, IB_urban_P2. Ultimately, six posets were produced: (Counties_P1, IB_human_P1), (Counties_P1, IB_water_P1), (Counties_P1, IB_urban_P1), (Counties_P2, IB_human_00_15), (Counties_P2, IB_Water_P2), (Counties_P2, IB_urban_P2). Accordingly, six Hasse diagrams were produced for the available data.

In the present study, the comparison of the counties/banners, characterised by LD drivers, can be explained as follows:

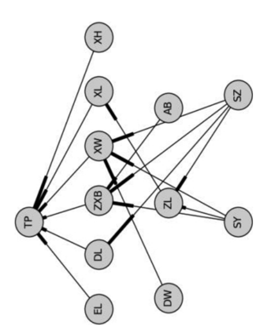
$$\begin{cases} x \geq y & <=> & qi(x) \geq qi(y) \quad \forall \quad qi \in IB \\ x \leq y & <=> & qi(x) \leq qi(y) \quad \forall \quad qi \in IB \\ x \| y & & \text{else} \end{cases} \tag{3}$$

When x ≥ y or x ≤ y, county x and y are comparable; when x||y, county x and y are incomparable.

In a Hasse diagram, a set of objects in the same vertical position is called a "level". "Chains" indicate a sequence of totally ordered elements, in which no incomparability exists. Chains can be used to trace the dominant drivers of LD with regard to the input data. A maximal element is one that has no other element further above, and it is usually drawn at the uppermost level of the diagram. A minimal element has no other element further below, and it is usually positioned at the lowest point of the diagram (see 2.3.3 and Fig. 3). An element x∈X that is not comparable to any other element and that simultaneously fulfils the definition of both a maximal element and a minimal element is called an isolated element (Hilckmann et al., 2017; Tsonkova et al., 2015; Voyslavov et al., 2013). In this study, the maximal element indicates a

Table 2 (*continued*)

(c) Urbanisation/industrialisation



County	Distance to urban land 1975	Distance to rural settlements 1975	Distance to road 1975	Distance to mine 1975	Distance to urban land 2000	Distance to rural settlements 2000	Distance to road 2000	Distance to mine 2000
XH	0.87	0.60	0.34	0.00	0.82	0.58	0.77	0.87
AB	0.43	0.45	0.61	0.14	0.36	0.41	0.55	0.00

Note: the isolated elements EL, SY, and SZ in Table 2b could be positioned at any level.

The input data of HDT

County Name	Durban 2000	Drural 2000	Droad 2000	Dmine 2000	Durban 2015	Drural 2015	Droad 2015	Dmine 2015
	2000-2015 Urbanisation indicators							
DW	0.50	0.75	0.80	0.82	0.49	0.70	0.71	0.84
XH	0.83	0.60	0.66	0.86	0.88	0.49	0.65	0.81
AB	0.32	0.56	0.59	0.25	0.26	0.45	0.39	0.35
SZ	0.00	0.22	0.00	0.00	0.00	0.04	0.19	0.00
EL	0.96	0.00	0.87	0.97	1.00	0.46	0.87	1.00

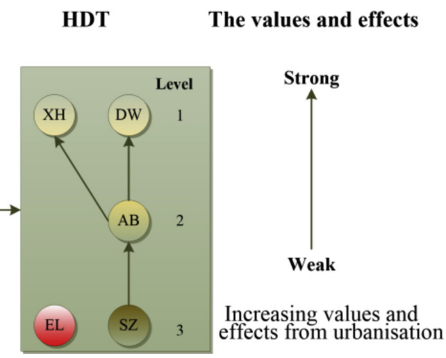


Fig. 3. An example of how HDT was applied for urbanisation between 2000 and 2015 in this study (using input data from Appendix 1-1). Note: XH, DW, AB and SZ are county names.
EL as an isolated element can be positioned at any level.

driver that had a dominant effect on LD in the county (large values for driver attributes), and the minimal element indicates that the driver has little influence on LD (small values for driver attributes). Isolated elements are not comparable with any other elements.

Before applying POR, all indicators have to be "normalised" and then "oriented". All indicators have to be normalised to the [0, 1] scale by using Eq. (4) (Tsonkova et al., 2015):

$$qn_i(x) = \frac{q_i(x) - q_i min}{q_i max - q_i min} \tag{4}$$

qn_i is the value of the indicator; $q_i$max and $q_i$mim are the maximum and minimum values of the respective indicator.

Since not all indicators contribute equally to the aim of the ranking, it is crucial to consider the orientation of all indicators before they are ranked. This also creates a conceptual link between the (normalised) values and the actual effect for each driver. The orientation of all the drivers is listed in Table 1. For the human disturbance group drivers, the effects of population and livestock increase with the growth of population and increasing livestock density. For the water condition group drivers, the effects of temperature increase with temperature, while the water body effects increase as distance from the water bodies increases, and the effects of precipitation decrease as precipitation increases. One could argue that surface water bodies attract livestock and would then foster grassland degradation, but this degradation occurs only at a very small scale, and on surfaces also closely related to mining development in Inner Mongolia (Li et al., 2012; Tao et al., 2015). For the urbanisation/industrialisation group, the effects of the four drivers decrease with distance. We are aware that rural-urban migration, as an important urbanisation process, can also indirectly show positive effects on LD, e.g. people leaving the grassland areas to move to urban areas, seeking better social conditions. However, this effect is difficult to measure, in contrast to the negative, direct effects. Also, when rural people move to urban areas, the individual grassland properties are not always completely abandoned. Landholders rent out the grassland, which is continuously used for grazing. In a bid to keep in line with other previous studies (Wang et al., 2017), we retain the interpretation of urbanisation as a negative effect. Since we now have a group of drivers which increase with the measure and another group that decrease with the measure (distance to urban land, rural settlement, road, mining and precipitation), we need to harmonise the two groups. For this purpose, we inverted the latter group as $qin_i(x) = 1 - qn_i(x)$ (see S1).

This study classifies orientation as either "strong" or "weak", where "strong" indicates that the driver has a strong effect on the LD process (strong objects are located in the upper levels of an HD), while "weak" indicates that the driver has a small impact on LD (weak objects are located in the lower levels). In the normalised value space between 0 and 1, 0 indicates the weakest possible effect, and 1 the strongest.

2.4.3. An example of a Hasse diagram application in this study

As an example, Fig. 3 shows how the HDT is used in this study. We extracted urbanisation data from the 2000–2015 period for five counties and analysed the eight selected indicators (distance to urban, rural, roads and mining areas for the two phases) simultaneously (Fig. 3, left). Each county is represented by a circle, and the relationships between different counties are represented by lines with an arrow. XH and DW are located in Level 1 with the largest value of all eight indicators, which means that LD in both counties is significantly close to these four drivers and affected by urbanisation. SZ is located in Level 3, with smaller values of these indicators, with points at no effect through urbanisation. Three levels are visible in this example.

EL is an isolated element. With the lowest value of distance to rural areas in 2000 (Drural_2000), no comparability exists with other counties (Fig. 3, in red). In addition, a total of five chains are present in this example: (DW, AB, SZ), (XH, AB, SZ), (DW, AB), (XH, AB) and (AB, SZ). These chains indicate an existing comparison of the urbanisation effects for the respective counties. All indicators are ordered weakly (all indicators sorted from the largest to the smallest value) along this chain (from bottom to top). All in all, in this example, urbanisation is the major driver in XH and DW, while the impact of urbanisation in EL is not shown clearly. The HDT was implemented using Python (Wieland, 2018).

3. Results

3.1. Changes in land degradation drivers in Xilingol

In an attempt to explain the land degradation that has occurred during the past 40 years, we analysed all nine previously selected drivers for the Xilingol area. Linear regression was used to explore the dynamics of population and livestock in both periods (Fig. 4). The total population has increased dramatically since 1975, and the growth rate did not change much over the whole period (Fig. 4a); however, total livestock (in sheep units) increased at an average rate of 32.0×10^4 sheep units per year in the 1978–2000 period, but then decreased at a rate of 6.4×10^4 per year between 2000 and 2015 (see Fig. 4b). Fig. 5e and f show that the median values of livestock density and population density in the LD area initially increased and then decreased in these two periods. Both urban and rural areas have developed in the past four decades, especially in Phase 2 (P2, see Fig. 4c). However, the distance from LD to the nearest urban or rural area (Fig. 5a and b) initially decreased and then increased over the three dates under investigation (1975, 2000, 2015), respectively. Water bodies, population and livestock experienced a similar trend. The area of water bodies shrunk by 184.7 km^2 and 1509.0 km^2 over the two periods (see Fig. 4c). Fig. 5g shows that the median value of the distance between an LD area and water bodies initially increased and then decreased at the three points in time. This is mainly due to the disappearance of water bodies after

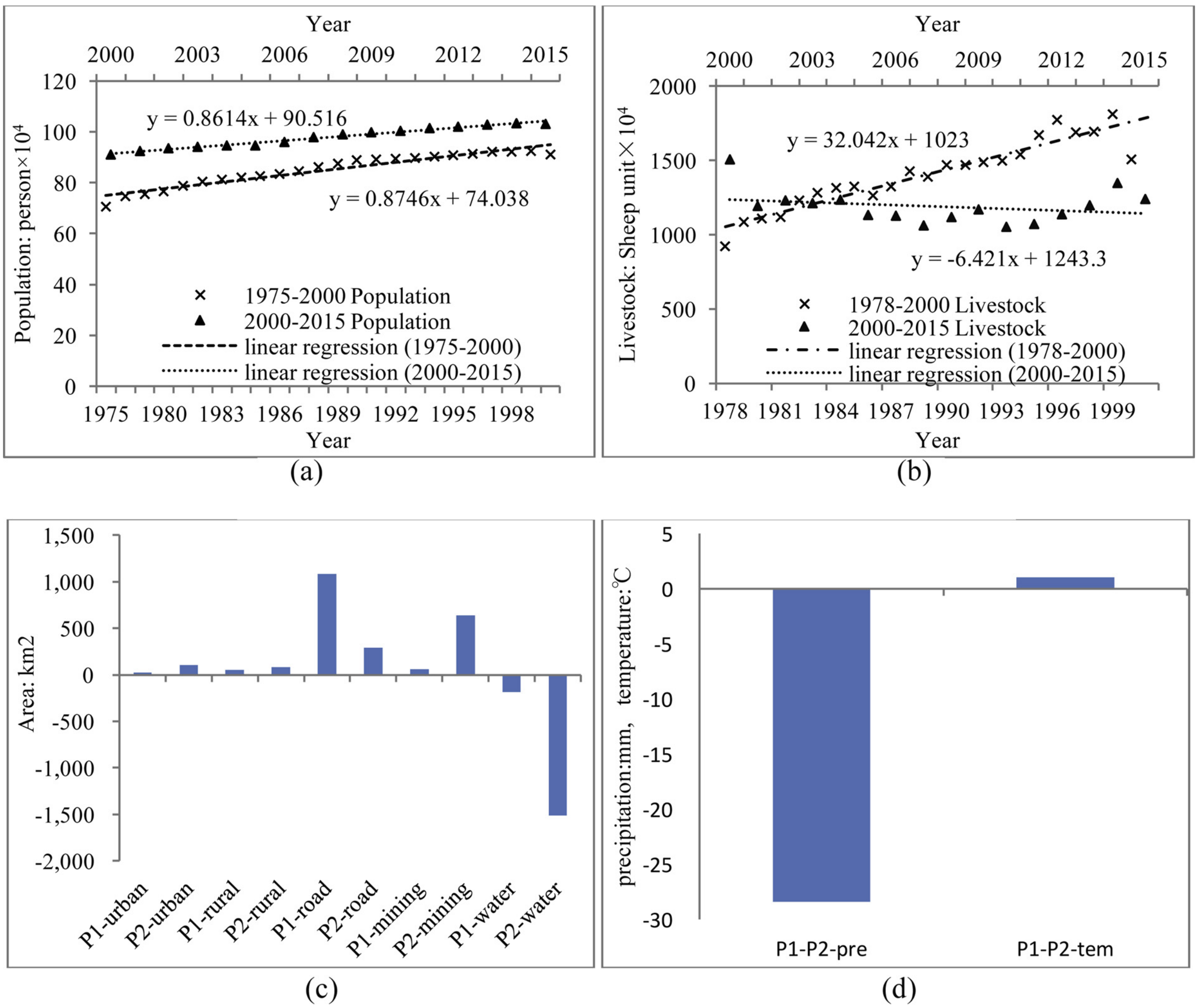


Fig. 4. The change in drivers in Xilingol between 1975–2000 and 2000–2015. a) Population, b) Livestock, c) Net area change of urban and rural centres, and roads, mines, surface water bodies, d) Change in precipitation and temperature.

2000. This transition process is itself a degradation process (Batunacun et al., 2018).

The rate of increase of road and mining areas reached a maximum in both phases. Fig. 5c and d shows that the median value of the distance from an LD object to roads and mining decreased at all three points in time, which means the results indicate that over time, LD objects and roads/mines became increasingly closer to each other. When comparing the two periods, the average growth-season temperature also increased (1.0 K), while total annual precipitation decreased (28.4 mm; Fig. 5h and i).

3.2. Partial order ranking of LD drivers

3.2.1. Partial order ranking of LD drivers during the 1975–2000 period

We analysed the levels, chains, structures and incomparable aspects of counties to identify the order of effect for the three factor groups on LD (Table 2). Based on the obvious difference in population density and livestock density in all counties, we now focus on two chains with different causalities that were extracted from the data.

To explore the significant effects from human disturbance more deeply, it was necessary to establish a criterion for the values in this group; when the values fell below 0.1, the effects were ignored. Eleven counties experienced strong effects from livestock density in 1975/78–2000 (except for EL, with zero values in both 1978 and 2000, see Table 2). Based on this, in six grassland counties (XH, DW, XW, SY, SZ and AB), the livestock density was the unique dominant driver. We call the chains that connected these six counties the "dominant livestock" chain ({XH, XW, SY, SZ}, {XH, XW, DW, SZ} and {XH, XW, AB}), where the effect from livestock density decreased along these chains. In contrast, the counties of DL, TP, ZXB, ZL and XL had higher effect values for population and livestock density (see Table 2a). We called the chains that connected these five counties the "dominant population and livestock" chain ({TP, XL}, {TP, ZL}, {DL, XL}, {DL, ZL}, {ZXB, XL} and {ZXB, ZL}). Both population and livestock density were the dominant drivers for LD in these five counties, and their effect decreased along these chains. EL was a special county, in that it only had high values for human population density. With respect to the spatial distribution of human disturbance drivers, the northern counties (DL, TP, ZXB and XH) suffered significantly from human disturbance; in the agro-pastoral transitional counties (DL and TP) in particular, they were the dominant drivers for LD.

The Hasse diagram for water conditions (Table 2b) revealed only three levels (the lowest having only one element) and three isolated elements (EL, SY and SZ). This means the Hasse diagram is weakly ordered and, correspondingly, there was no obvious spatial pattern in the impact of water conditions on LD. Climate factors, especially temperature, were the most involved indicators in these three counties (see Table 1 orientation and Table 2b).

The Hasse diagram for urbanisation (Table 2c) exhibited four levels and no isolated element, which means we can characterise this Hasse

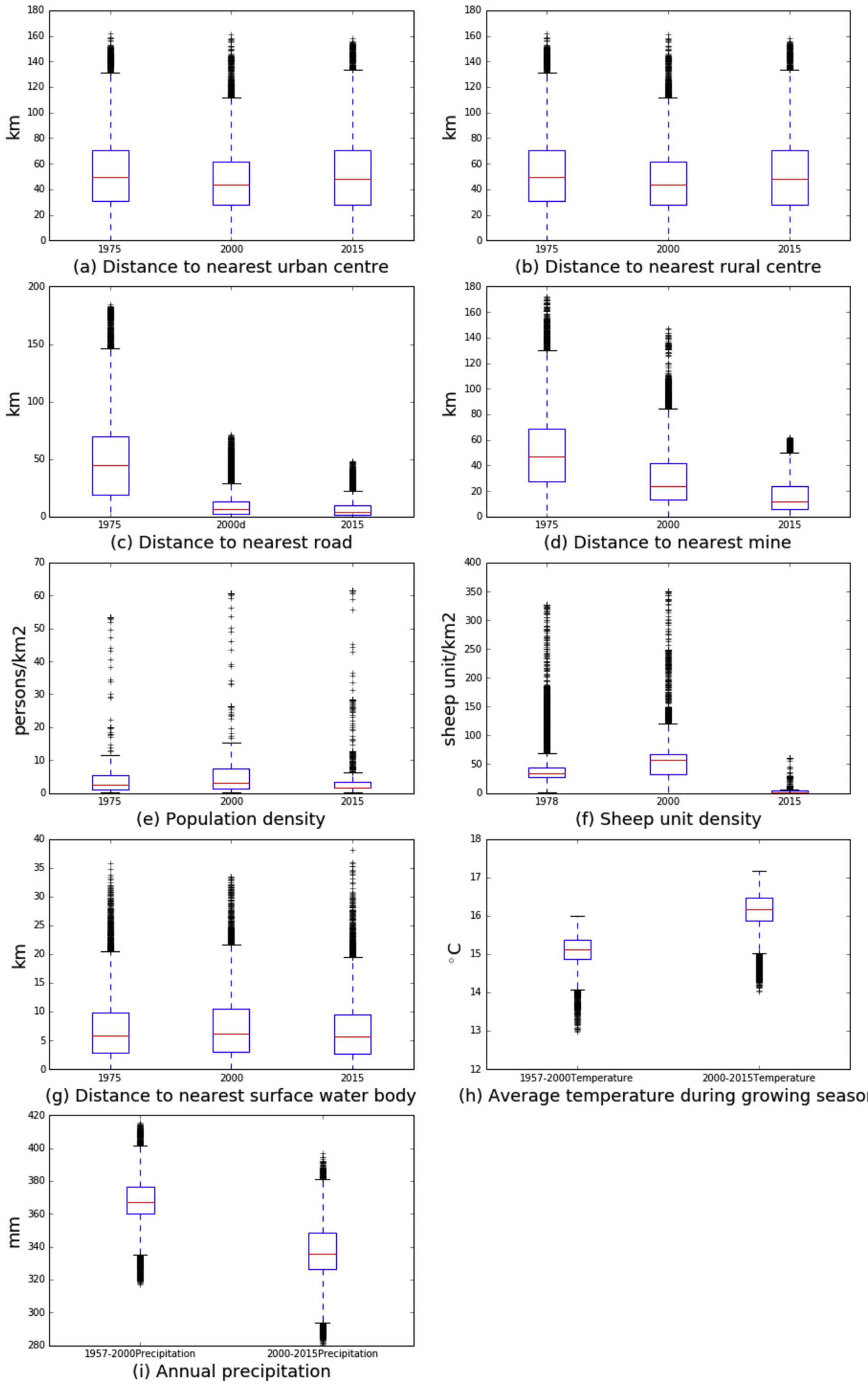


Fig. 5. The state of land degradation drivers at three points in time (temperature and precipitation given as averages between points in time due to their temporal variability).

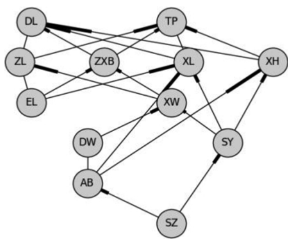
diagram as being strongly ordered. We identified the agro-pastoral counties, TP and DL, as being strongly affected by urbanisation, as they are positioned in the upper levels (TP: Level 1, DL: Level 2, see Table 2c), while SY and SZ, dominated by sparse grassland and placed in the lowest level, were only nominally affected by urbanisation.

3.2.2. Partial order ranking of LD drivers during the 2000–2015 period

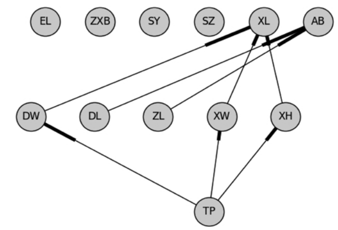
For human disturbance factors, the situation seems to have remained the same during this period. XH, DW, XW, SY, SZ and AB still only suffered from high pressures of livestock density. Table 3a shows that the chains {XH, AB, SZ}, {XH, SY, SZ}, {XW, DW, AB, SZ} and {XW, SY, SZ} are “high livestock” chains. The chains that connect TP, DL ZL, ZXB and XL ({DL, TP}, {DL, ZXB}, {DL, XL}, {TP, ZL}, {TP, ZXB}

Table 3
Hasse diagrams and their input data for all indicator groups from 2000 to 2015.

(a) 2000–2015 Human disturbance

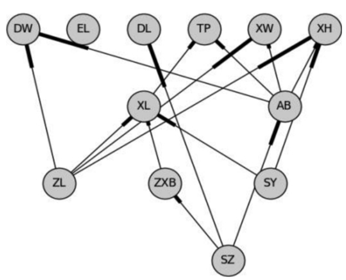


(b) 2000–2015 Water conditions



County	Population density 2000	Population density 2015	Sheep unit density 2000	Sheep unit density 2015	Distance to water 2000	Distance to water 2015	Precipitation 2000–2015	Temperature 2000–2015
DW	0.01	0.02	0.29	0.48	0.42	0.28	0.29	0.80
EL	0.05	0.11	0.00	0.00	1.00	1.00	0.85	0.22
DL	0.44	0.47	0.82	1.00	0.49	0.41	0.37	0.35
TP	1.00	1.00	1.00	0.99	0.00	0.00	0.00	0.49
ZL	0.12	0.12	0.48	0.77	0.60	0.25	0.58	0.42
ZXB	0.18	0.18	0.36	0.81	0.56	0.26	0.52	0.48
SY	0.04	0.04	0.17	0.28	0.98	0.99	0.49	0.31
SZ	0.00	0.00	0.11	0.25	0.64	0.62	1.00	0.00
XW	0.05	0.06	0.33	0.73	0.21	0.26	0.51	0.75
XL	0.14	0.20	0.30	0.39	0.48	0.45	0.70	1.00
XH	0.08	0.09	0.28	0.84	0.40	0.31	0.56	0.54
AB	0.01	0.01	0.26	0.39	0.64	0.66	0.72	0.42

(c) 2000-2015 Urbanisation/industrialisation

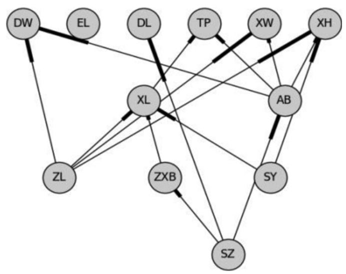


County	Distance to urban land 2000	Distance to rural settlements 2000	Distance to road 2000	Distance to mine 2000	Distance to urban land 2015	Distance to rural settlements 2015	Distance to road 2015	Distance to mine 2015
DW	0.50	0.75	0.80	0.82	0.49	0.70	0.71	0.84
EL	0.96	0.00	0.87	0.97	1.00	0.46	0.87	1.00
DL	0.96	0.85	0.48	0.62	0.88	0.82	0.78	0.93
TP	1.00	1.00	1.00	1.00	0.92	1.00	1.00	0.79
ZL	0.44	0.19	0.38	0.72	0.38	0.00	0.32	0.49
ZXB	0.62	0.31	0.69	0.60	0.69	0.16	0.50	0.44
SY	0.58	0.27	0.30	0.71	0.53	0.12	0.00	0.49
SZ	0.00	0.22	0.00	0.00	0.00	0.04	0.19	0.00
XW	0.50	0.69	0.88	0.93	0.53	0.66	0.85	0.88

(*continued on next page*)

Table 3 (*continued*)

(c) 2000-2015 Urbanisation/industrialisation



County	Distance to urban land 2000	Distance to rural settlements 2000	Distance to road 2000	Distance to mine 2000	Distance to urban land 2015	Distance to rural settlements 2015	Distance to road 2015	Distance to mine 2015
XL	0.82	0.54	0.88	0.86	0.78	0.47	0.83	0.79
XH	0.83	0.60	0.66	0.86	0.88	0.49	0.65	0.81
AB	0.32	0.56	0.59	0.25	0.26	0.45	0.39	0.35

Note: the isolated elements EL, ZXB, SY and SZ in Table 3b could be positioned at any level, as well as EL in Table 3c.

and {TP, XL}) are “high population and livestock” chains. EL, with a high value for human population in 2015, suffered more from this driver. Spatially, the southern counties suffered more effects from both population and livestock (both located in the upper level, see Table 3a). The agro-pastoral counties (DL and TP) were especially affected by human disturbance factors, while the grassland counties (located in lower levels) were dominantly affected by livestock density.

For water conditions during 2000–2015, only three levels emerged, with a small number of chains as well as four isolated elements, indicating that the driver of water conditions is overall weakly ordered. During this period, XL and AB continued to experience significant impact from water conditions, while this driver’s effect on XH decreased compared to the earlier period. The agricultural areas (DL, TP) remained largely unaffected (Table 3b). EL, SY, SZ and ZXB are isolated elements in this period, of which the climate factors in EL, SY and SZ, especially temperature, are mostly responsible for this incomparability (Table 3b).

Urbanisation drivers increased the number of ordered elements in the uppermost level from one (in the earlier period) to five, indicating an obvious impact of urbanisation across Xilingol after 2000 (Table 3c). Dense grassland areas (DW, XW, XL, XH) suffered much more from urbanisation, followed by the moderately dense and sparse grassland areas in the northern part of the league (ZL, SY, SZ). The agro-pastoral areas DL and TP were also among those counties that suffered greatly from urbanisation in this period. EL is an isolated element, with a zero value for indicator Drural_2000 (Table 3c).

3.2.3. Order rankings for all drivers of land degradation in the two periods

In this section, we transformed all comparison results into ranks for all drivers for the two periods; Section 2.4.3 above laid out an explanation for the orientation of the levels. Driver groups that were found to be dominant were positioned at the top of the diagram. The identification of levels and isolated elements from the Hasse diagrams can help us to understand the major drivers of LD at the county level. During the 1975–2000 period, human disturbance was the dominant driver group in eight counties (ZXB, DL, XW, SY, TP, ZL, XH and SZ; see Fig. 6a). Human disturbance had the strongest effect in ZXB, DL, TP and XH, followed by XW, ZL, SY and DW. Water conditions constituted a dominant driver group in six counties, where XL, AB and XH were affected most by water conditions, followed by XW, ZL and DW. Urbanisation was a dominant driver group in TP, followed by XW, EL and SZ. Ultimately, human disturbance was the only dominant driver group in ZXB, DL and SY; water conditions served as the major driver group in XL, AB and DW; both human disturbance and urbanisation were major driver groups in TP and SZ; and human disturbance and water conditions were the dominant driver groups in ZL and XH. In XW, all three groups affected LD similarly (Fig. 6a).

After 2000, the dominant drivers changed significantly in all counties. Human disturbance was now the major driver group in five counties (ZXB, DL, TP, ZL, EL), of which DL and TP suffered the most significant effects (Fig. 6b). Water conditions emerged as the major driver group in three counties: XL, AB and ZL. Urbanisation was the dominant driver group in seven counties, of which DL, XW, TP, XH and DW were influenced most heavily, followed by SY and SZ. Above all, human disturbance was the major driver group in ZXB and EL; the water conditions group was the dominant driver group in XL and AB. Human disturbance and urbanisation were the major driver groups in DL and TP; urbanisation was the dominant driver group in XW, XH and DW; and water conditions and urbanisation were the major driver groups in XL and AB (see Fig. 6b).

After ranking all the drivers, we compared the ranking results for both periods. The major driver groups in TP, XL, AB and ZL remained unchanged. Otherwise, as a more general observation, the effect from urbanisation increased, and has now become more dominant than human disturbance, and water conditions effects decreased after 2000. In the agro-pastoral areas, effects from human disturbance and urbanisation either remained steady (TP) or increased (DL) after 2000.

4. Discussion

Partial ordering resulted in a ranking of all drivers that had the greatest impact on LD in Xilingol. The identification of these levels, as well as the combination of maximal, minimal and isolated elements, facilitates scientific understanding of the major drivers of LD in this region. Since national policies have an important effect on stakeholders’ decisions and land management practices, it is necessary to analyse the relationships between these drivers and policies under the current situation. Fig. 7 depicts a summary of the vast literature relating to policy, human disturbance, urbanisation and water conditions for the period from 1978 to 2050. The graphic only covers the topics and causal relationships at the focus of this paper.

4.1. Policy structures in Xilingol since 1978

A total of eight national and/or regional policies have been carried out in this region since 1978. We have grouped all policies into three categories according to their aims and real-world effects (see Table 4 for abbreviations): (1) Economic Stimulus policies (ES): ER, HPRS; (2) policies that Control Human Pressure (CHP): RGG, FGMU and PES, aiming to reduce livestock and users on grassland; and (3) polices that Combat LD (CLD): GFGP, BTSSCE and TNSFS, which have attempted to improve environmental conditions (e.g. by afforestation; Table 4). Before 2000, the Household Production Responsibility System (HPRS) was enacted, radically changing the system of property rights. The objective of the HPRS was to assign livestock and grassland to the herder’s household; the goals were to both stimulate economic development and to protect the environment in Xilingol. However, the HPRS has been shown to have led to rather short-term economic development and to further degradation of grassland (Li and Huntsinger, 2011). Since 2000, six national environmental protection policies have been implemented in Xilingol. Their aims and time scale are summarised in Table 4.

4.2. The relationship between drivers of land use changes and political policies

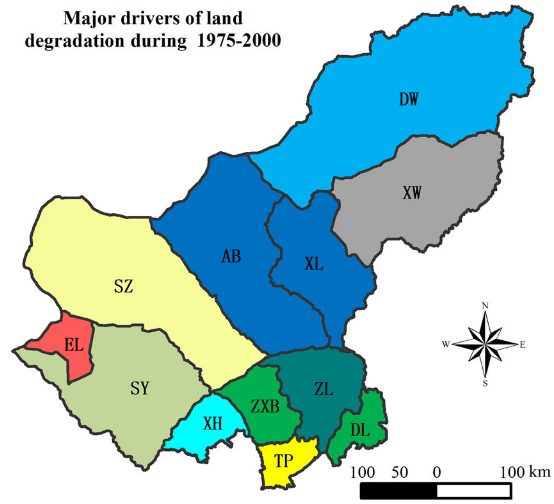
4.2.1. Drivers related to economic reform policies up to 2000

During the 1975–2000 period, human disturbance was the dominant driver in eight counties (ZXB, DL, TP, XH, XW, ZL, SY and SZ). The economic reform in 1978 and the HPRS in the 1980s led to significant increases in population and livestock density (Jiang et al., 2006), which was shown to be the major cause of degradation in this area. Economic reform encouraged husbandry development, which is why a considerable number of Han people migrated to the grassland areas of Xilingol in this period (Jiang et al., 2006). Due to this policy intervention, long-term overgrazing became the direct cause of grassland degradation, behind which we find demand for livestock products on the part of the increasing population to be the ultimate driving force (Kawamura et al., 2005; Zheng et al., 2011).

4.2.2. Drivers related to ecological protection policies after 2000

After 2000, ecological protection polices had a considerable impact on the local environment. Some of the identified links between polices, human disturbance (population and livestock) and land degradation developed in a similar pattern. For one thing, ecological policies had a direct impact on human disturbance factors. Many previous studies have suggested that the CHP policies have worked effectively in part of Xilingol (Du et al., 2016; Li and Huntsinger, 2011; Waldron et al., 2010), and the partial order results in our study indeed show that the effects caused by human disturbance have largely decreased. At the same time, livestock numbers have also decreased (Fig. 4b). The four counties in which human disturbance continuously causes LD (DL, ZL, TP and ZXB) are located in the south of Xilingol (ZXB, DL, TP, ZL, EL,

Ranking of drivers (1975-2000)				
County	Human disturbance	Water condition	Urbanisation	Dominant drivers
ZXB	1	2	2	Human
DL	1	3	2	Human
XW	2	2	2	Human,water and urban
SY	3	ISO	4	Human
XL	2	1	2	Water
AB	3	1	3	Water
TP	1	2	1	Human and urban
ZL	2	2	3	Human and water
XH	1	1	2	Human and water
DW	3	2	3	Water
SZ	4	ISO	4	Human and Urban
EL	3	ISO	2	Urban



Ranking of drivers (2000-2015)				
County	Human disturbance	Water condition	Urbanisation	Dominant drivers
ZXB	2	ISO	3	Human
DL	1	2	1	Human and Urban
XW	3	2	1	Urban
SY	4	ISO	3	Urban
XL	2	1	2	Water
AB	5	1	2	Water
TP	1	3	1	Human and Urban
ZL	2	2	3	Human and Water
XH	2	2	1	Urban
DW	4	2	1	Urban
SZ	6	ISO	4	Urban
EL	3	ISO	ISO	Human

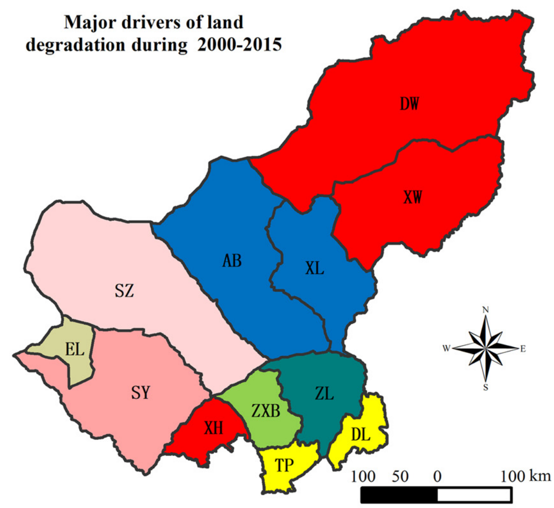


Fig. 6. The major drivers and their ranking in each county between two periods (a: 1975–2000, b: 2000–2015). Note: The colour represents the identified type of most dominant drivers. ISO refers to an isolated element, indicating no dominant driver for the respective category in this county.

see Fig. 6b), where population figures are high and grassland resources are limited (Sun et al., 2017; Wuyinga and Haishan, 2017). These circumstances have resulted in poverty, reinforcing negative trends. More livestock was kept in the hope of generating income, which led to further degradation and further poverty – a vicious cycle of poverty and LD. Consequently, in these areas, reducing population pressures would be the radical answer. Recommendations have included support for continuing to carry out anti-poverty policies, encouraging stock-breeding diversity and developing more livestock-related industry to alleviate poverty and degradation (Wuyinga and Haishan, 2017; Zheng et al., 2011).

The identified link between human disturbance, urbanisation and LD after 2000 is obvious. The increasing population accelerated urban and rural expansion and road development. In addition, the development of coal mining and related heavy industry, such as coal-based power generation and petrochemical processing, also accelerated as a consequence of road construction and the increase in urban areas with cheap labour. After 2000, all the policies that were meant to stimulate the economy targeted livestock restrictions (in the form of grazing bans or maximum stock rates) and the relocation of herders (partly into cities), which subsequently drove urban land expansion. Development in urban as well as rural areas and the accompanying road construction mainly took place in high-quality grassland areas and led to grassland fragmentation, seriously threatening the region's biodiversity. Regulations like the "Xilingol Urban Development Plan" (also known as the Xilingol master plan) were set up to alleviate this problem, but there still is a lack of policies or regulations that effectively protect the areas surrounding urban/rural land. Our findings show that after 2000, the average distance from both urban and rural population centres to LD has increased (see Fig. 5a and b), which means that the ecological protection measures have worked effectively in this respect. However, since unwanted side effects have occurred, related measures such as grazing bans or fencing requirements must now be taken to protect the remaining grassland areas close to emerging cities or rural population centres.

Mining has emerged as the top source of income in Xilingol. After a set of restrictions related to stockbreeding (e.g. grazing bans and rotation grazing, see Table 2) had been enacted, mining became the major industry in 2008, which it has been ever since (Yang et al., 2014). Coal mining from surface mines consumes considerable land area, while the subsequent petrochemical processes require large quantities of water. Mining also causes the most dramatic and rapid land use changes, affecting soil, groundwater aquifers, and surface waters, due to the removal of topsoil, the enormous use of water, and the deposition of huge amounts of excavation material on the surface (Qian et al., 2014). Our results demonstrate that after 2000, urbanisation and industrialisation –

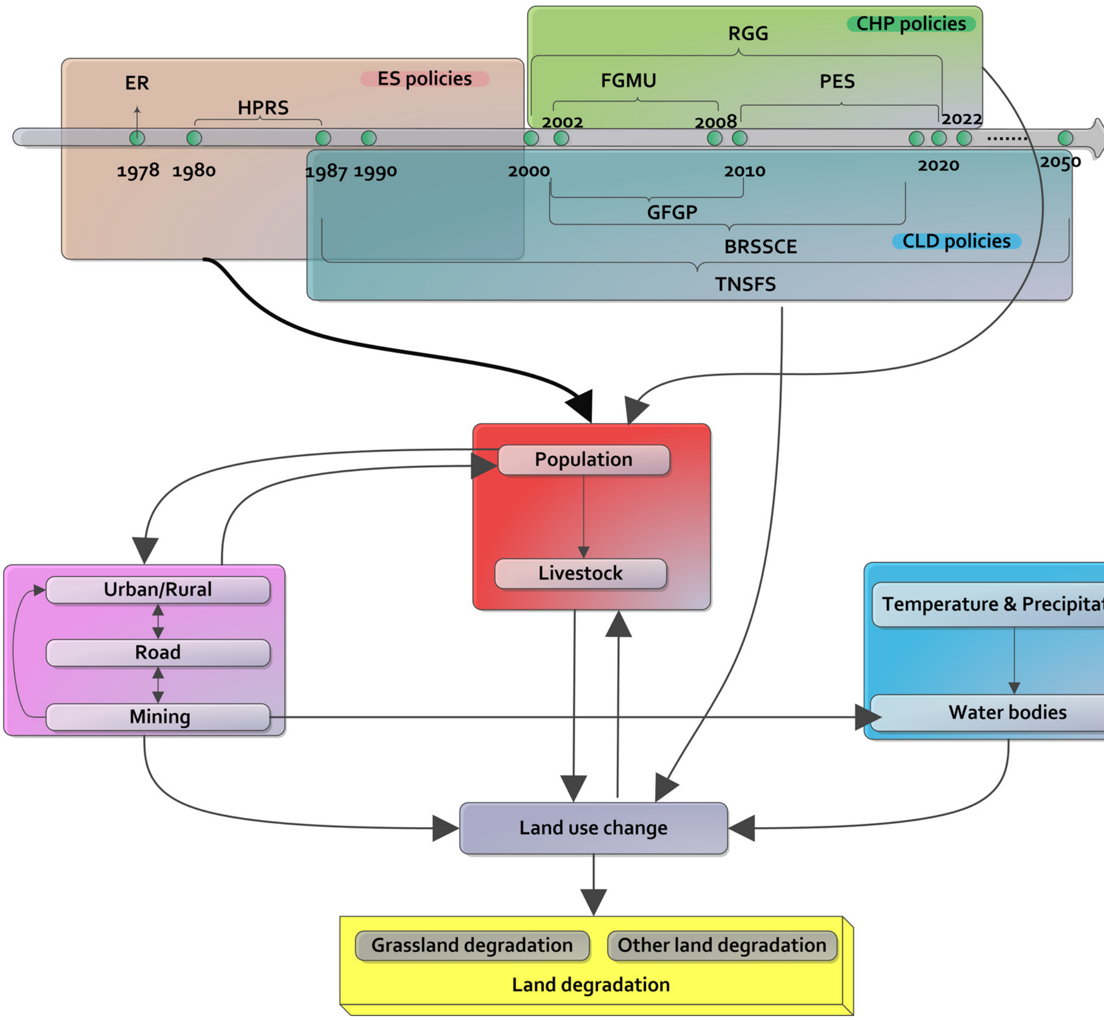


Fig. 7. Schematic concept of the interplay between policy, land degradation and related drivers. Note: The green dots represent the point in time at which policies were implemented.

i.e. mining – has become the dominant type of driver of LD in Xilingol in seven counties (DL, XW, SY, TP, XH, XW and SZ). Yang et al. (2011) reported that rapid urbanisation and industrialisation had altered the ecological footprint dramatically.

Water availability in the Xilingol region is an important biophysical factor that determines the natural productivity of grasslands, but that also ensures the quality of life for the people themselves. The causality between mining, water conditions and land degradation is also significant. Our findings show that water bodies have shrunk considerably, while the climate has become warmer and drier. Increased water consumption through mining, higher evapotranspiration at warmer temperatures, and less rainfall have consequently all lead to the reduced availability of water resources, demonstrated by lower groundwater tables and decreased surface areas of lakes and lower levels of river discharge. In fact, groundwater levels in Inner Mongolia have been falling for decades, even though this development is not seen as being outside natural fluctuations at this stage (Brutsaert and Sugita, 2008; Davi et al., 2013). Statements concerning water availability are greatly impaired by the very limited number of stations that monitor long-term groundwater levels on the Mongolian plateau. Tao et al. (2015) suggested that surface water shrinkage in grassland areas is mainly caused by the development of coal mining. Moreover, Qian et al. (2014) showed that coal mining, coal-based power generation and petrochemical processing had all been using extremely high quantities of water. To meet the water demands of coal-based industries, local rivers and their tributaries have been dammed, and many wells have been dug (Tao et al., 2015). At the same time, the climate itself has had a negative effect on the size of surface water bodies. There have been attempts to actively restore the ecological value ofdesertified land by replanting. However, geologists assume that parts of the areas lost to desertification will remain that way forever (Yang et al., 2015).

4.3. Application of partial order theory

It is crucial to compare the different factors of LD to evaluate and adjust current ecological policies, and provide information for future decision-making processes. Since the factors of LD are complex and cannot be reduced to single components, earlier studies applied different multi-criteria decision methods, such as the Analytic Hierarchy Process, Cluster Analysis, Logistic Regression or the HDT (Kardaetz et al., 2008; Lin et al., 2014; Memarbashi et al., 2017; Müller-Hansen et al., 2017). Principle Component Analysis (PCA) is also well-suited to identifying the first and second major drivers (components) for land use change based on available driver data (Yan-fen et al., 2008). However, PCA is a linear approach, and for this reason it is not suitable for detecting the non-linear relationship between drivers and effects between different counties. In contrast, HDT is able to extract information from comparable elements, as well as extracting information from incomparable elements as well. For example, Fig. 2 indicates that XH and DW are incomparable elements; while both counties suffered from urbanisation pressures, the means were different (XH was more affected by urban area expansion, while DW responded more to road and mining

Table 4
Description of major national policies in Xilingol.

Periods	Policy Groups	Policy Name	Time Period	Measures	Aims
Pre-2000	ES	The reform and opening-up policy (henceforth: Economic Reform, ER)	1978 to present	(1) Economic reform (2) Economic and societal opening	Accelerate economic development
		Household Production Responsibility System (HPRS) (Akram et al., 2009; Li et al., 2007)	1980s to 1990s	Assignment of grassland property to an individual household	(1) Control overgrazing (2) Help rangeland restoration (3) Improve livestock production
	CHP	Fencing Grassland and Moving Users (FGMU) (Akram et al., 2009; Bijoor et al., 2006)	2002 –2008	(1) Grazing restrictions (grazing ban or rotational grazing) (2) The transfer of inhabitants (3) Promotion of high-yield agriculture (4) Imports of high-value livestock	Restore heavily degraded grassland
		Returning Grazing to Grassland (RGG) (Liu, 2017; Rahimi, 2016)	2000–2020	(1) Grazing ban (2) Rotational grazing (3) The setting of a deterministic stocking rate	(1) Restrict grazing (2) Conserve heavily degraded grassland by sowing grass
		Payments for Environmental Services (PES) (Démurger and Pelletier, 2015; Meyer et al., 2015; Uthes et al., 2010)	2010–2020	(1) Grazing prohibition subsidies (2) Grass grazing balance subsidies (3) Grass seed subsidies (4) Performance appraisal awards	Achieve a win-win situation in terms of both environmental protection and poverty alleviation
	CLD	Beijing-Tianjin Sand Source Control Engineering Project (BTSSCE) (Zeng et al., 2014)	2001 to present	(1) Afforestation (2) Sandy land restoration	Reduce wind-induced soil loss and related sandstorms in the Beijing-Tianjin megacity belt
		"Three Norths" Shelter Forest System (TNSFS) (Cao, 2008)	1987–2050	Afforestation	Mitigate desertification
		Grain for Green Programme (GFGP) (Liu et al., 2014)	2001–2010	(1) The restoration of cropland to forest or grassland (2) The conversion of barren land to forest on steep slopes by providing farmers with food and cash subsidies	Convert croplands on steep slopes to forest or grassland

development). Moreover, the method allows for a "data-driven" analysis on the one side, and a combination with expert knowledge on the other, e.g. during the orientation process or the identification of chains or isolated elements.

In addition, analysis of the Hasse diagram structure, its priority elements and its pattern of indicators together revealed the major drivers of LD over territory and time. In this research, we collected nine drivers and grouped them into three categories, comparing and ranking these major drivers at the county level. This process enabled us to derive recommendations according to the dominant drivers in each county. These results can provide important information to develop scenarios of different land use models (e.g. CLUE-S, LandSHIFT, alucR) which address the regional variation in dominant drivers in the study area.

Moreover, analysis of HDT is relatively flexible, and not only depends on the goals, but also the tolerance of stakeholders. For example, in Fig. 3, EL is an isolated element within the urbanisation drivers group, with the smallest value of Drural_2000 and the largest values of Durban_2000, Droad_2000, Dmine_2000, Durban_2015, Droad_2015, Dmine_2015 (see Fig. 3). If we reset the tolerance of the effects from this driver group, we could remove rural drivers in 2000 and even in 2015. As a consequence, EL would become the uppermost element and urbanisation would turn out to be the dominant driver for LD in EL.

However, in the present study, all effects from all drivers have been fully considered and no driver was ignored. In addition, in this study, we have selected a non-robust statistical method to process the data (normalisation, see Eq. (4)). Alternatively, a standard scalar or a binary scalar could also be used to explore the data. Furthermore, due to limitations on the acquisition of rural population data (the earliest statistical records for rural population in this region date back to 1995), this study was unable to distinguish between rural and urban population. For this reason, we used total population as an indicator, but if better data were available, this indicator could be revisited.

5. Conclusions and suggestions for future policy development

In this study, we identified the drivers of land degradation and their dynamics in Xilingol, and analysed the variation of the dominant groups of drivers over territory and time at the county level. We found that population figures and urban, rural, road and mining areas increased between 1975 and 2015, while numbers of livestock initially increased and then decreased before and after 2000. Water bodies have decreased over the past four decades, and the climate has become warmer and drier in this region, with increasing temperature and decreasing precipitation. These results indicate that the effects of direct human disturbance on LD have declined, and the coincidence of this decline with the implementation of major ecological policies suggests that these policies have indeed been the major cause of this decrease (we showed that the average distance from urban/rural centres to LD increased after 2000). However, at the same time, the expansion of rural and urban centres, road construction and mining have further increased, and in the investigated period after 2000, these factors developed into the predominant drivers for LD, especially in non-agricultural areas, even outperforming the effects of decreasing water resources (though these still remain an important driver). In agro-pastoral areas (TP and DL), human disturbance was dominantly responsible for LD in both periods.

While previous ecological reform and conservation policies have been an obvious success with respect to the target for which they were developed, unwanted side effects have nevertheless occurred. Much of the urbanisation and industrialisation that has been observed after 2000 can also be attributed to these policies. As these emerging factors continue to drive LD along different pathways, it is now necessary to continue working on measures that protect the remaining grassland areas close to emerging cities or rural centres, such as the implementation of grazing bans or fencing. Keeping this political pressure high is essential for the protection of the ecological resources and the cultural heritage of Xilingol and the Mongolian Plateau, but it can only lead to the desired outcome if it is accompanied by additional measures that use different levers. In counties where the direct effects of human disturbance and urbanisation dominate, policy may need to address poverty, such as through increasing stockbreeding diversity and the development of more livestock-related and tourism-related businesses. In counties in which LD continues to be driven by high livestock numbers, livestock control needs to be continuously enforced, e.g. through policy measures such as grazing bans, imports of high-value livestock, deterministic stocking rates and grazing prohibition subsidies that have already been launched in Xilingol.

For the development of more sustainable land use in Xilingol with a focus on grassland ecosystem protection, two further targets for political action are clearly identifiable:

Against the background of diminishing water resources, the government should focus on developing clean energy concepts, and improve coalmining technologies to reduce water consumption and conserve the precious groundwater resources that the local society so critically relies on. When the use of water for energy supply and mining conflicts, policy has to work towards improved water use efficiency of industrial processes, support for green procurement in the energy sector and the integration of water resources as an equally important target in decisions on energy and mining development. This is particularly challenging, as water resource management requires multinational planning and policy implementations at the catchment or groundwater basin level.

It has also become evident that the mining industry needs to be targeted more directly in future policy developments. This may include increased political pressure to improve the efficiency of coal mining in general (not only with respect to water use), which may lead to providing constant coal production with a reduced number of active mines. More rigid mining planning, e.g. regulating the number of mining licences and thereby reducing the overall number of mines that are operating at the same time, may prove helpful. Policy development could also work to increase awareness about the ecological reclamation of completely exhausted mines, especially in the counties that currently exhibit the most active coalmining industry – AB, DW, XW and XL – and provide the required political pressure to enforce such restoration (Sun et al., 2017). In the end, more intensive migration and settlement control seems necessary to organise labour availability for the mines and to organise urban and rural expansion more effectively. This should be organised with respect to the county-specific characteristics that exist among the distinct areas of Xilingol as a result of varying drivers, which we have been able to show by means of POR.

In sum, we have demonstrated that drivers for LD in the Xilingol area have exhibited distinct temporal dynamics over the last 40 years, with a spatial pattern showing that different drivers dominate different areas in the League. This calls for county-tailored policy measures to combat further grassland degradation and to sustain the ecological value and cultural heritage of Xilingol, while maintaining sufficiently high income levels and standards of living.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.landusepol.2019.02.013.

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