Resilience of Tibetan Pastoral System in Modernisation

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Abstract

On the Tibetan Plateau, there is a long history of animal farming practices. Although Tibetan pastoralism had been successful in the past to support the population, the problems of increasing demand and impact in the face of more scarce resources and global climate change are challenging pastoralists. The problem is even more pronounced in the Tibetan Plateau's unique natural and socioeconomic conditions.

Based on the perception of the problem, the Chinese government started a reform programme aiming at changing the nomadic practices in Tibet. Tibet today is in transition, not only in terms of pastoralism, but also that of culture, of institutions, and of economy, nevertheless the transition in pastoralism as a livelihood and source of income will have significant implications.

The usefulness of the resilience concept in examining a complex system's innovation, development, disturbance and reorganisation makes them suitable tools in the study of historical changes and the future of Tibet, as the area is under human management, and subject to the influence of changes in nature and external policies.

In this study remote sensing and mathematical modelling approaches are used to assess ecological resilience in the region. The advantage of remote sensing allows the researcher to observe and analyse a large area as well as recent changes, and to examine the spatial pattern of these changes. The model simulates the dynamics of the grassland system given

the current condition. The key functions linked to the system's resilience can be examined in this model and provide information on the system's sustainability. The simulation shows that the nomadic pastoralism system can better adapt to disturbances of known intensity and frequency than the sedentary style. However, the trend of climate change and population increase may require a change of organisation and practices for the system to be sustained.

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Contents

List of Figures

List of Tables

Chapter 1

Introduction

There is a long history of animal farming practices. The domestication of animals accompanied the human race's transformation from hunter-gatherers to agriculturalists since about 9,000 years before present (BP) (Shanklin 1985, Clutton-Brock 1999). Due to its outstanding adaptability and diversity, this time-proved means of production remains one of the most active and important sectors in the whole agriculture society. It is estimated that extensive pastoral production occupies 25% of the world's land area and produces 10% of the meat used for human consumption (Blench 2001). Pastoral products today serve as a major source of protein and to a lesser extent of clothing materials. Pastoralism has been adopted by people from a wide range of arid environments or areas with scarce source, ranging from Africa to Middle East to Tibet and to Scandinavia (Fratkin 1997). In these areas aridity usually forbids other forms of agriculture, which depend on a high level of soil moisture and constant irrigation. For people living in those areas, pastoralism provides them with necessary livelihood. However, as living conditions improve, pastoralist population increases. This, along with increasing world demand of protein, creates pressures on pastoralism and grassland ecosystem, and may cause overgrazing and a decrease of productivity. Although pastoralism is successfully supporting over 20 million pastoral households worldwide

(Blench 2001), the problems of increasing demand and climatic impact in the face of more scarce resources, such as useable pastures and water, and global climate change are challenging pastoralists wherever they are.

In China's southwest, the Tibet Autonomous Region (TAR) is also facing such problems. The problem is even more pronounced given the Tibetan plateau's unique natural and socioeconomic conditions. Tibetan pastoralism is distributed almost all over the plateau, although the actual practices may be different in different areas. In relatively low southern and eastern parts pastoralism co-exists with agriculture, while in high-altitude and arid northern and western parts pastoralism exists mainly in nomadic or transhumance forms. The transhumance forms are based on a rotation system and availability of winter and summer pastures, and short-term movements in order to find better grassland patches. The high altitude of above 4000 m on average and short growing season of no longer than 5 months limit the output from pastoralism in the northern and western Tibetan Plateau (Miller 2002), while the state's policy is trying to encourage Tibetan pastoralists to develop pastoralism not only as a livelihood but also as a means of gaining income (Bauer 2005, Manderscheid 2001, Manderscheidt et al. 2004), by establishing factories and putting Tibetan pastoral products into local and national markets. Meanwhile, Tibetan traditional pastoralism institutions and practices, especially those involving conserving a large number of livestock, are considered by the government and some researchers as irrational and detrimental to the environment, causing ecological problems such as overgrazing and desertification (Levine 1999, Richard 2003*b*). It is argued by the governing authorities that such an unorganised and outdated production mode should be replaced by modernised system with allocated pastures and improved infrastructures in order to avoid severe losses in harsh winters and to control the phenomenon perceived as widespread grassland degradation (Sheehy, Miller and Johnson 2006). Based on this assertion, the State is orchestrating a series of projects, including fencing pastures and setting clearly defined pastures allocated to individual households, organising pastoralists into villages, and constructing infrastructures. Inevitably this in return stirred arguments that the mobility and traditional culture are being threatened (e.g. Wu 1999, Sheehy, Miller and Johnson 2006). Tibet today is essentially in transition, not limited to that of pastoralism, but also that of culture, of institutions, and of economy, nevertheless the transition in pastoralism as a major livelihood and source of income will have a significant role in this reform of the TAR. Whether the traditional pastoral culture should be preserved, whether Tibetan people can enjoy improved economic conditions, and whether modernisation is at the cost of adaptability and resilience are the Tibetan people and researchers' concern.

It is desirable to be able to answer these questions raised in a large and complex system as pastoral social-economic system. The difficulty nevertheless lies in the fact that the behaviour of such systems is determined by many interacting factors. One example is in fishery, where the overfishing of herbivorous fish not only reduced yield from the population but also caused uncontrolled growth of macroalgae and killed corals, which has much more profound consequences (Botsford et al. 1997). As Holling (1996*b*) notes, a simple black or white choice focusing on only one or two of the factors in decision making may bring unexpected results, or "surprises". Even if many factors are considered in decision making, the ones that are overlooked may still cause surprises. Small changes in known factors may cause a nonlinear response of the system. A framework that prepares for surprises and nonlinear changes in decision making is needed. The purpose of the framework determines that the traditional approach in ecology, characterised by linear and tractable mathematical models, is no longer applicable. Instead, the study of the system's behaviour in the face of sudden changes calls for the development and application of nonlinear mathematics, and more importantly a nonlinear understanding of complex systems, acknowledging the limitation of traditional linear models and the significance and commonness of sudden, disruptive changes.

The complexity and non-linearity of ecosystems has been observed and acknowledged by the community of ecologists and environmental managers (e.g. Kay and Schneider 1994, Sparks 1995, Carpenter and Gunderson 2001). However, a unified and operational paradigm to describe and evaluate such complexity has been missing. As a result, management of ecosystems and the coupled social systems has to rely on theories based on linearity assumptions, causing unexpected and undesirable results. There have been various attempts to address the nonlinearity of ecosystems, such as cellular automata models (Balzter et al. 1998), and nonlinear time series models (Pascual and Ellner 2000), but these attempts are not organised in a systematic way to form a framework. In his observation of some self-contained ecosystems, Holling (1973) also found that the system shows nonlinear, unstable but resilient behaviours. Furthermore, Holling points out that the assumption of a stable state which the system tends to go back to is valid only in the vicinity of a given equilibrium point, called the domain of attraction. The shifting between domains of attraction can be sudden and nonlinear, and often means drastic change of a system's defining functions and features. Examples of such change of functions include rangeland turning into desert, or clear lake becoming turbid. If a system shifts from one domain of attraction to another, it may not be able to support its original species, or continue to provide ecosystem services. For human-managed systems, an ideal character should be that they do not easily change their functions in the face of changes, i.e. they remain resilient to external and internal changes. Holling thus formalised his concept of resilience as: "a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist." (Holling 1973, p.17). Since the introduction of this new concept of resilience in 1973, it has helped the development of other concepts and approaches such as adaptive management, and greatly changed the way people look at changes in complex systems.

The usefulness of the resilience concept in examining a complex system's innovation, development, disturbance and reorganisation makes the resilience concept a suitable tool in the study of the TAR's historical changes and future, as the area is under human management, and constantly subject to the influence of changes in nature and external policies. The use of the resilience concept and the domain of attraction approach allows researchers and managers to understand what the key driver of state shifting is, what is needed for such a shift and what needs to be done if the shift in state is to be avoided (Janssen and Anderies 2002). It also helps researchers to understand how well the old and new system can adapt, not only to current conditions, but also other drastically different conditions caused by sudden environmental or policy change. This knowledge, in essence is the understanding of why and how the system moves in the domain of attraction and what is the volume of the domain of attraction. The detailed description and review of the resilience paradigm and its development will be included in this thesis.

Inspiring as the resilience concept is in the study of complex systems, a significant amount of work is still required before it can be informative. In practice, resilience is still assessed by mathematical models, or alternatively by analyzing species interactions and defining functional groups. The mathematical modelling method aims to assess the "size" of the domain of attraction directly. The basic mathematical tools employed nowadays are still largely based on continuous mathematics such as calculus, but the models are constructed in a way that incorporates discontinuity and hysteric behaviours. The species interaction approach involves defining functional groups and sorting species or social entities into these groups, therefore one can tell whether any of these groups may have significant changes that alter a system's key functions and attributes. Both of the two approaches require a considerable amount of information. The complexity of ecological and social systems render it nearly impossible to develop a unified methodological framework for resilience assessment, which hinders the adoption of a resilience approach. Even so, assessment of resilience has being conducted in various locations and settings and has provided information for ecosystem management and social development. For example, McLauchlan (2006) uses the resilience concept to evaluate the impact of changes in soil organic matter caused by agriculture, while McGuire and Sperling (2008) analysed the impact of seed aid on farmer's ability to cope with stress by examining its effect on resilience.

In this study the researcher uses remote sensing and mathematical modelling approaches to assess resilience in the TAR. This is because the focus of the study is not only on the ecosystem, but more on the social-economic system that depends on grassland and pastoralism, including the implication of more frequent natural disturbance, the settlement of pastoralists, and the effects of migration and privatisation. Because the environment is heavily influenced and managed by humans, looking at species and their respective functional groups provides little information about the system's resilience. Ultimately human management in various spatial and temporal scales determines in part the fate of local socioecological system and production practices. In this case a modelling approach is more adequate. Based on the researcher's understanding of the Tibetan pastoral system, the model will focus on the impacts of productivity and management options.

Ideally, it would be very desirable to include local people's knowledge and oral history in the study, as well as observing their actual pastoral practice. However, the difficulty of data collection was exacerbated by its remoteness, high altitude environment and the problem of the researcher's identity as a Chinese international student studying in a university in the United Kingdom. Considering these constraints, it has been necessary for the researcher to adopt a slightly different approach to the study. The advantage of remote sensing allows the researcher to observe and analyse a large area as well as its recent change history. More importantly, remote sensing enables the researcher to examine the spatial patterns of various variables and their implication for the area's resilience (Frohn 1997, Luers et al. 2003). The model used in the study can be spatialised using remotely sensed data. Although the model cannot completely replace closer observation of the area, it is hoped that within practical limitations, it can still provide some insights into Tibetan pastoralism's resilience and adaptability that are not obtainable by other means.

The aims set for the study are:

- To gain an in-depth understanding of how grassland ecosystem have adapted to external drivers such as climate change over the recent decades;
- To investigate the implications of natural and institutional changes on the plateau;
- To evaluate the sustainability of local rangeland and its ability to support livestock and pastoral livelihoods under different management styles/regimes.

In order to achieve the aims, the objectives of the study include:

- Evaluating productivity and viability of the Tibetan grassland ecosystem, in order to define its current state;

- Identifying the characteristics of disturbances in the area by analysing the fluctuation of vegetation indicators using remotely sensed imagery;
- Modelling the response of grassland ecosystem in various possible scenarios;
- Evaluating the resilience and sustainability of the Tibetan grassland socio-ecosystem by synthesizing available information.

1.1 Structure of following chapters

The organisation of the rest of the thesis is as follows: the geography of the area and history of pastoralism in this area are reviewed in Chapter 2. Chapter 3 reviews some theories and approaches based on which the goal and methodology of this thesis were developed. Chapter 4 describes the methodology used in the thesis, including data sources, spatial analysis and modelling. Chapter 5 illustrates the results. Chapters 6 and 7 discuss the implication of the results and conclude with the findings of the study.

Chapter 2

Background

In order to understand the Tibetan pastoral system, along with its uniqueness and limits, the geography of the plateau should be understood in the first place. This chapter starts with an introduction of Tibet's location and topography, and goes on to describe the palaeoclimate and current climate in Tibet. The history of Tibet's traditional and evolving pastoralism and its interaction with state policies are covered in the second section.

2.1 Geography and climate of the area

The Tibetan Plateau is located in the western part of China, in the interior of the Eurasia Continent (Figure 2.1). The plateau is encircled by the Himalayan Mountains to the south, Hengduan Mountains to the east, Kunlun Mountains and Qilian Mountains to the north and in the west is adjacent to the Pamir plateau (Zhang et al. 2002). The plateau contains the whole TAR of China, as well as a large part of Qinghai Province and part of Sichuan and Yunnan Province. The area of the plateau within the Chinese border is 2.5724×10^6 km^2, which accounts for a quarter of China's total land area.

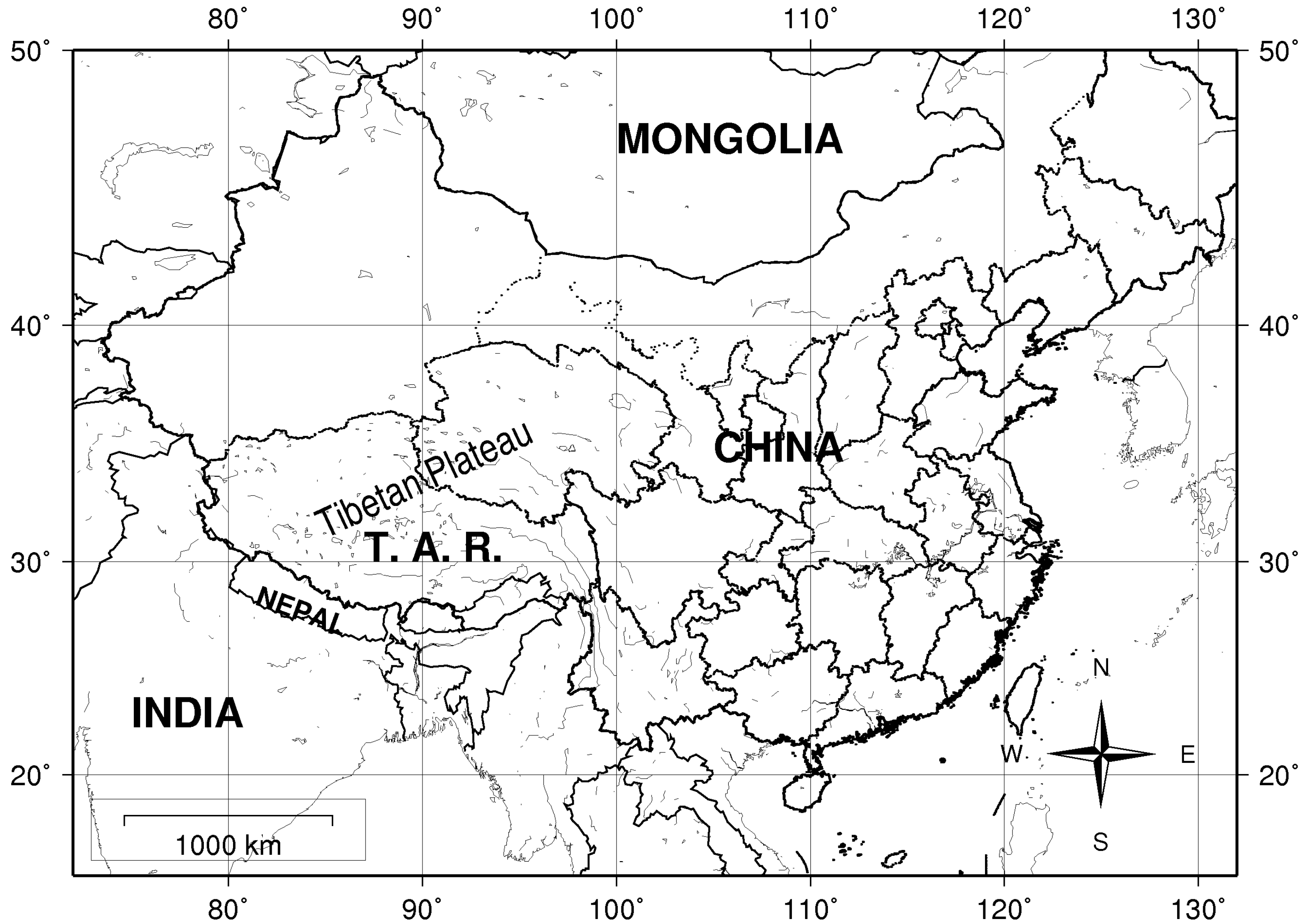


Figure 2.1: The location of the Tibetan Plateau in China. The map was drawn with Generic Mapping Tools (GMT) (Wessel and Smith 1991, Wessel 2007) using the Global Self-consistent, Hierarchical, High-resolution Shoreline (GSHHS) shoreline data (Wessel and Smith 1996).

2.1.1 Topography and waterbodies

The Tibetan Plateau is located at the edge of the Eurasia plate, where the crunching of the Indian plate caused the uplift of the plateau started about 13 – 14 million years BP (Turner et al. 1993, Coleman and Hodges 1995). The unequal speed of uplift and the force of South Asia subcontinent has resulted in the plateau's undulating topography. There are four major mountain ranges in Tibet, namely northernmost Aerhchin-Qilian Mountains, Kunlun-Bayan Kala Mountains, Kharakoram-Tanggula Mountains, and the Himalayas in the south (China Tibet Information Center n.d.). Aside from these mountains which align east to west, mountains in Eastern Tibet are mostly aligned north to south, such as Hengduan Mountains. The average altitude of the plateau is 4,000 m above sea level (asl.) but in different areas the altitude ranges from about 1,500 m asl. to over 5,000 m asl., while most mountains can reach over 6,000 m asl. Generally, the southern and eastern parts of the plateau are low with deep-cut ravines and some high peaks dotted, while the northern and western plateau is high and relatively flat (Figure 2.2). On the other hand, mountains of greater altitude are mostly part of the Kharakoram-Tanggula and the Himalaya Mountains in the south.

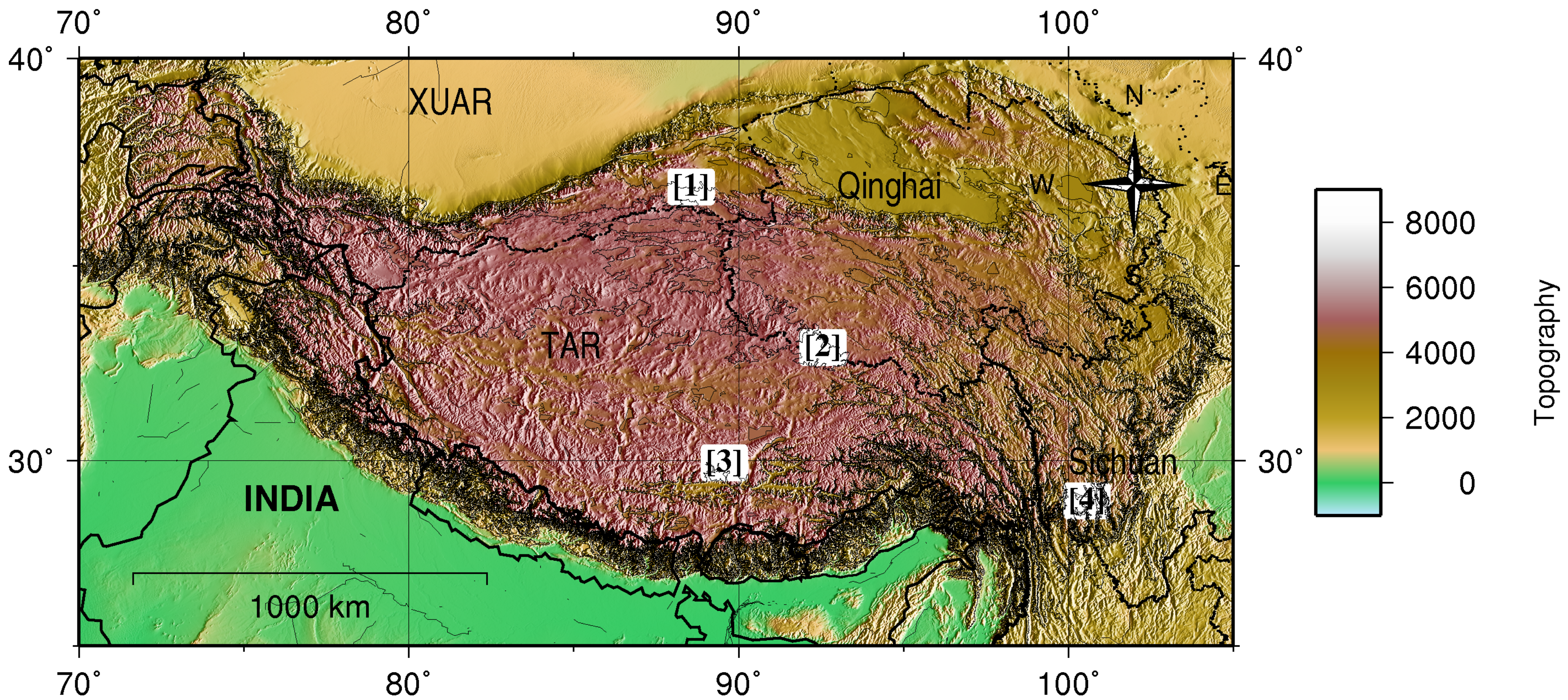


Figure 2.2: Topography of Tibetan Plateau and adjacent areas. The topography data is provided by Smith and Sandwell (1997). The baseline and borders were drawn with GMT and GSHHS database. Some major mountain ranges are marked on the map: [1] Kunlun Mt. [2] Tangula Mt. [3] Niangqen-Tanglha Mt. [4] Hengduan Mt.

The mountains and different altitudes divide the area into several sub-areas. The Nyangqin-Tanggla Mountains form the boundary of the Northern Tibet and the Central/Southern Tibet; a series of mountains and ravines define the Eastern Tibet; the Western Tibet is delimited from the Northern Tibet by elevated ground, and its southern boundary is marked by Mount Kailash. Within these sub-areas, various topographical features have created complicated climate and ecosystem distributions. The Yarlung Tsangpo valley in the Southern Tibet is arid to the west and becomes wetter as it goes toward the east. The valleys and the mountains surrounding them create large altitude differences and a gradient of conditions that support unique ecosystems. Chang Tang in the Northern Tibet is relatively flat with rolling hills and lakes scattered throughout the landscape. Vegetation in this area is sparse, while barren rock and soil dominate the ground, yet in places with higher groundwater table large areas of grazing lands can be found (Aldenderfer and Yinong 2004).

The altitude gradient from west to east and the abundance of glaciers on the Tibetan Plateau determine that this area is the source of several major rivers in Asia, but the flow of most rivers in Tibet is limited due to the large evaporation/precipitation ratio and flat terrain, such as the upper sections of the Yellow River and the Yangtze River. An exception is River Brahmaputra in the south, thanks to larger altitude difference in this area.

A number of lakes are scattered over the Tibetan Plateau and constitute an important feature of the area's natural environment. These lakes are believed to have been formed during the glacial epoch and are fed mainly by glacial meltwaters or in the south of the Tibetan Plateau by monsoonal rains (Aldenderfer and Yinong 2004). Over 1,600 lakes are of sizes above 1 km^2, while Qinghai Lake, Nam Co, Siling Co, Tangra Yumco and Yamzho Yumco are over 1,000 km^2 in area. A saline lake belt can be defined by the western part of the Karakorum-Himalaya mountains and a line connecting Qinghai Lake and Yamzhuo Yumco. This region belongs to the eastern section of the saline lake belt in the northern hemisphere, but Qinghai Lake is outside the belt. The belt can be further divided into 7 districts (Figure 2.3), from north to south: Qilian inflow district, Qaidam inflow district, Kumkol inflow district, Hoh Xil inflow district, Qiangtang inflow district, North Tibet inflow district, and South Tibet inflow-outflow district (Zheng et al. 1997). Large fresh water lakes that can serve as water supply to human and livestock populations are much fewer on the plateau and their volumes are limited, but many small ones are scattered over the plateau as a result of its undulating terrain.

2.1.2 Palaeoclimate and climate

The palaeoclimate record on the Tibetan Plateau before the Holocene has relatively few data available. The direct record of the Pleistocene comes mainly from ice core samples, whose record ability is limited by the condition and preservation of the glacier. Among the ice core records, the Guliya ice core holds an exceptionally extensive record that has been dated to as early as 120 thousand years (kyr) before present (BP) (Yang et al. 2006). But aside from this, the reconstruction of the palaeoclimate on the Tibetan Plateau has to rely on inference based on other data collected in surrounding areas and known climatic events.

The early glacial period dates back to 90 – 50 kyr BP, and it is believed that regional climatic conditions were possibly as extreme as during the last glacial maximum (LGM) (Brantingham et al. 2003), as glacial advance in this period exceeds that in LGM. During this period the extent of ice on the Tibetan Plateau may have reached 297,000 km^2 (Derbyshire et al. 1991). Between 45 and 25 kyr BP there was an interglacial period characterised by cool summer temperature and increased precipi-

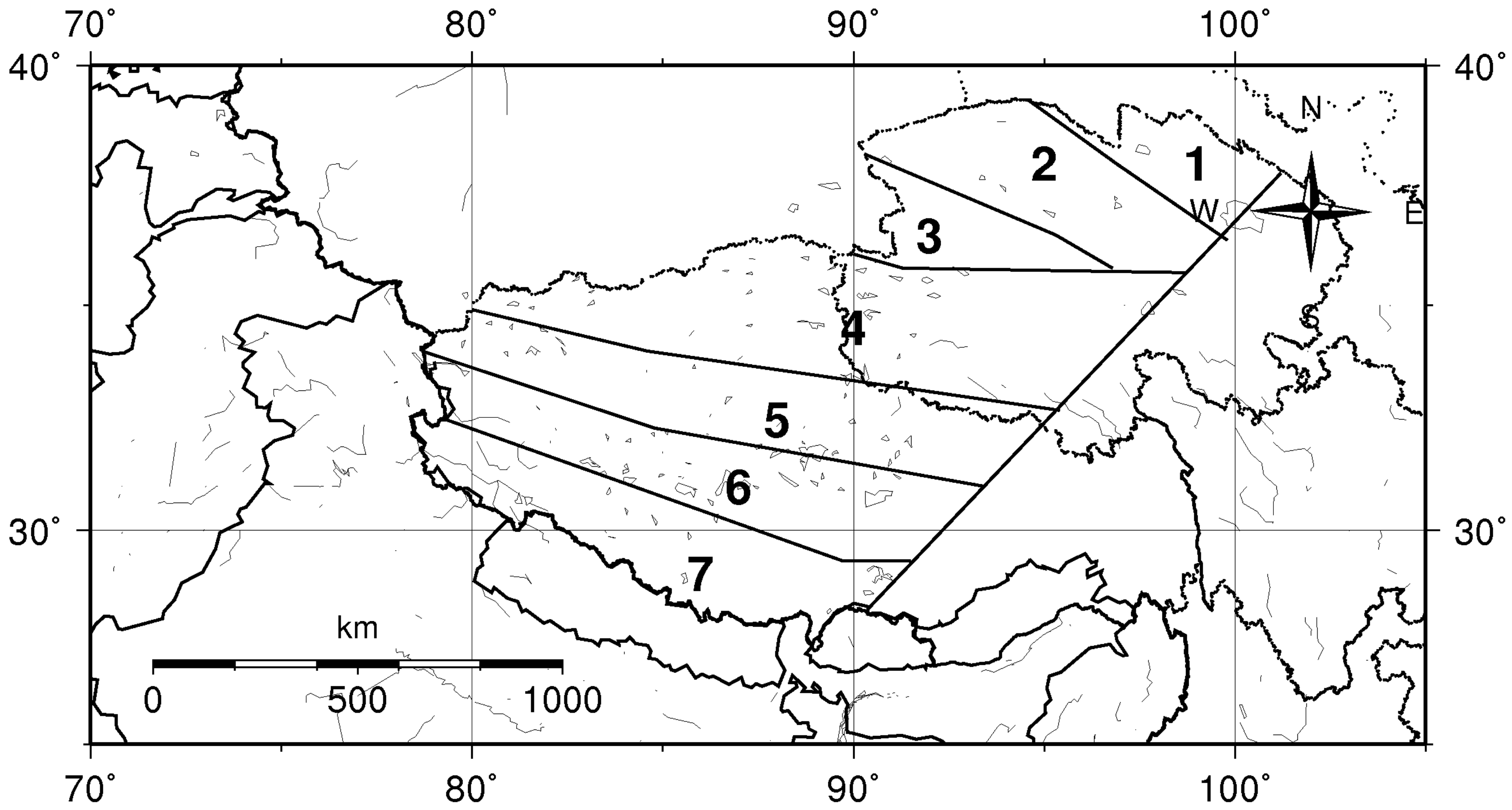


Figure 2.3: Qinghai-Tibet plateau and lake districts. 1: Qilian inflow district; 2. Qaidam inflow district; 3. Kumkol inflow district; 4. Hoh Xil inflow district; 5. Qiangtang inflow district; 6. North Tibet inflow district; 7. South Tibet inflow-outflow district. Redrawn from Zheng et al. (1997). Boundary and waters map data obtained from State Bureau of Surveying and Mapping of China (2008).

tation. As a result, lake water levels in the numerous lakes across the region rose in this period and some desert was turned steppe (Brantingham et al. 2003).

The LGM (22 – 18 kyr BP) was characterised by increased aridity, declined temperature and increased evaporation. As a result the lakes shrank in this period, and no glacial advance was recorded. The general pattern of glacier distribution at this time may be similar to that of the present day, with the east-west ranges dominating the distribution. In the post-LGM period some lakes re-entered an expansion phase but the deserts were not shrinking.

The glacial/interglacial transition took place in Tibet about 10,000 years BP. A variety of proxy indicators suggest that effective humidity reached a peak about 10,000 – 8,000 years BP, which was associated with a rapid rise in temperature on the plateau. The decreased snow and ice cover may have helped strengthen the monsoon (An et al. 2000).

The climate in the early to middle Holocene was warmer and wetter than at present (Gasse et al. 1991). But the central and western Tibet may have returned to cold, dry conditions at about 10,000 years BP, which is in contrast with other areas on the plateau (Lehmkuhl and Haselein 2000). This may be the result of different monsoon conditions in this area. Two ice cores from Dunde and Guliya record the climatic variations in the Holocene with high temporal resolution. The Guliya ice core showed that after the Younger Dryas cold event (11.5 kyr BP), temperatures increased, possibly due to the occurrence of a monsoon maximum (Ge et al. 2007), then dropped suddenly at 7,000 years BP. This warm phase started and ended earlier than in other places of the world. From 7,200 to 5,000 years BP it was relatively cold and dry (Wu et al. 2006), and the evidence suggests that the cooling might have led to the weakening of the Asian summer monsoon (Jin et al. 2006). Decreases in monsoon precipitation may have taken place and are recorded in Central Tibet lake sediment records (Morrill et al. 2006). Temperatures rose again after 5,000 years BP except for a cold phase from 3,500 to 2,500 years BP. Aridity increased after 3,000 years BP, with the period of maximum aridity on the central Tibetan Plateau occurring after 2,000 years BP (Wu et al. 2006). But this data is considered to only be reflecting climate changes near the boundary of the Tibetan Plateau. The interior of the plateau has much less data (Wu et al. 2006). The temperature changes from 16,000 years BP until the present day according to various sources is illustrated in Figure 2.4.

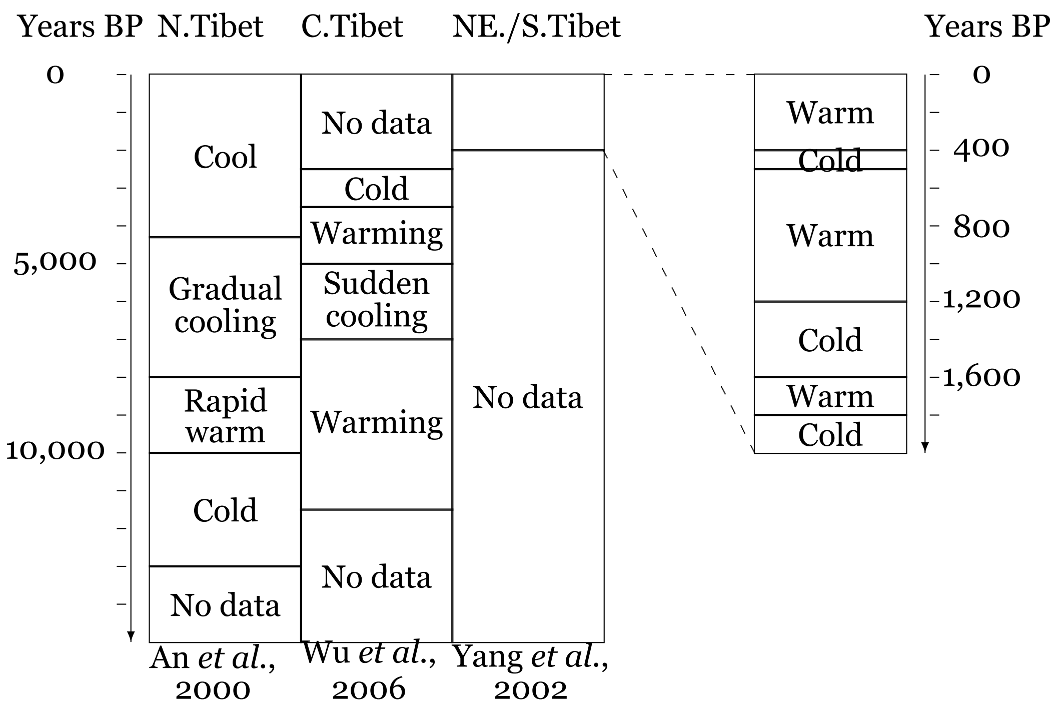


Figure 2.4: Climatic episodes from Holocene according to various sources

Aside from climate changes that cover a long time span, since agriculturalists and pastoralists colonised the plateau (see Section 2.2.1), there have been a few climate change events that took place on a relatively shorter time scale. Though these events are short in terms of geological time, they have had impacts on the region's ecosystem and socio-economic system. The oxygen isotope level in ice core samples collected from Dunde, Guliya and Dasuopo shows stable or decreasing trend for the last millennium (Thompson et al. 2003), showing that the temperature in this period is stable, with a few cooling events. The Guliya and Dunde ice core samples both recorded three cold events that took place around the 15th, 17th and 19th century, respectively. This is confirmed by other evidence, such as glacier moraine ridges observed in the vicinity, and temperature records in Shanghai since 1471 (Yao et al. 1997). The length and size of the moraine ridges also reveals information about the intensity and relative temperature change during the cooling event.

Moreover, lake sediment evidence shows that in Central Tibet a 100-year drought took place between 2,200 and 1,800 yr BP, and the July temperature dropped by 0.8 °C in the period between 700 to 300 yr BP. Due to these events' effects, the steppe/meadow ecotone in this area has shifted east and west several times in the past two millennia (Shen et al. 2008). There have been extensive studies indicating that the 20th century climate in Tibet is showing a significant trend of increased temperature and aridity. The evidence includes direct observation (Jones and Yoshino 1996), glacier retreat (He et al. 2003), permafrost temperature (Wu and Liu 2004), and tree-ring chronologies (Gou et al. 2007).

The Tibetan climate at present is characterised by strong seasonality and annual fluctuation in precipitation and temperature. This is because the area is under the control of various climate systems at different times of the year. The main systems influencing the climate include the Westerlies and South Asia Monsoon. In northern Tibet the westerly winds are an important circulation pattern throughout the year, which bring dry and cold air from the central part of the Asian continent to northwestern China (Bao et al. 2003). The westerlies are also responsible for bringing moisture to the plateau and form precipitation from October to May.

The geographical position of the convergence zone where the Atlantic westerlies meet the Asian monsoonal system depends on their relative strength. These strengths are determined by the intensities of the air pressure gradients over the North Atlantic, and the Siberian High Pressure Cell, respectively (Vandenberghe et al. 2006). The North Atlantic Oscillation (NAO) reflects the intensity of the westerlies. It has been reported that NAO has been in an extremely strong phase since 1980 (Yang et al. 2005).

The northern part of the Tibetan Plateau's weather system is mainly controlled by the westerlies. The zone axis of the northern westerly shifts between about 35° to 37 °N in glacial-interglacial cycles (Sun 2004). The dust and aerosols over the plateau are also related to the intensity of the westerly. As the westerly has weakened in recent years, the frequency of dust events in Tibet has also declined (Wang, Yao, Yang, Shen and Wang 2007). In spring dust is transported southward from the Taklamakan Desert and the Qaidam Basin by northwesterly surface winds. A study shows that the westerlies contribute about 25% of the total dust in the central Qinghai-Tibet Plateau (Xiao et al. 2002). However, the westerlies are blocked by Tanggla Mountains. Thus moisture and dust transported by the westerlies are significantly reduced in the southern part of the plateau.

In terms of temperature, the westerlies can bring above-normal temperature to southern and central Tibet (Yin et al. 2000). During winter, the cold plateau and relatively warmer air to the south create a strong temperature gradient associated with a westerly subtropical jet stream flowing to the south (Meehl 1992). The shift of westerlies influences winter precipitation in the form of snow, which in turn influences heat over the plateau and summer precipitation.

The spring and summer monsoon wind field is illustrated in Figure 2.5. Winter snow cover has an effect on the strength of the South Asia Monsoon. Excessive Eurasian snow cover consumes energy and reduces

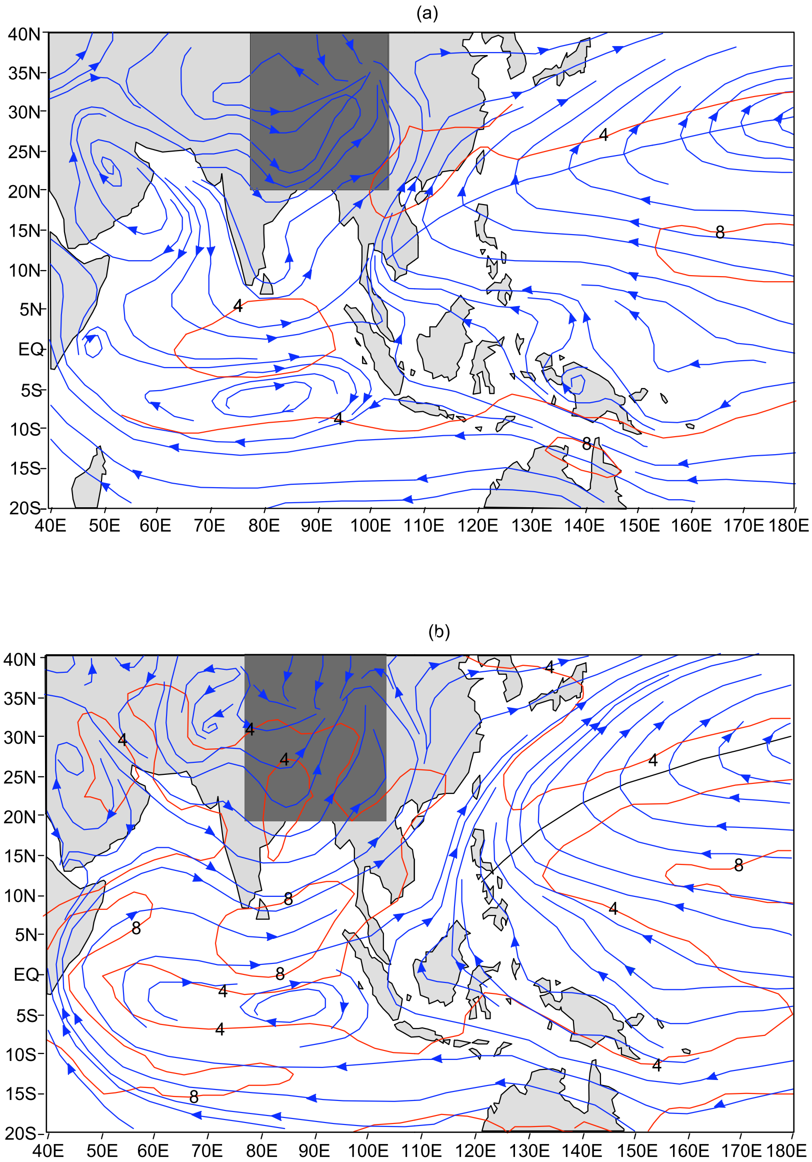


Figure 2.5: Climatological mean streamline and wind speed (m/s) in the periods of (a) May and (b) June. The dashed line represents the ridgeline of the subtropical high. The grey box indicates the location of the Tibetan Plateau. Adapted from Qian and Lee (2000)

the surface temperature over a broad region centred around the Tibetan Plateau. Reduced surface sensible heat flux reduces the midtropospheric temperature over the Tibetan Plateau. The result is reduced midtropospheric meridional temperature gradient over the Indian peninsula and a weakened monsoon circulation (Vernekar et al. 1995).

In a study of air temperature and precipitation over the plateau using data from 1951 to 1990, it was found that the anomalies recorded at the Lhasa meteorology station are of different sign from those recorded by three other stations in the eastern part of the plateau (Jones and Yoshino 1996). This is also attributed to the summer monsoon circulation.

The impact of the Indian monsoon on summer precipitation is most pronounced in the south and southeast of the Tibetan Plateau. The northeastern corner of the plateau is influenced by both the Indian Summer Monsoon and the East Asian Summer Monsoon. A study by Xu et al. (2007) have shown that the source of moisture in this area is controlled mainly by East Asia Summer Monsoon, while the intensities of the two monsoon systems are inversely related to each other.

There are also some other factors that influence Tibet's climate through their effects on the monsoon and westerlies, such as El Niño. The impact of El Niño events on the Tibetan Plateau is demonstrated by negative temperature and precipitation anomalies in the summer (colder and drier) and positive anomalies in the winter (warmer and wetter). Because of this, it is suggested that the impact of El Niño in winter and summer, under global climate change conditions, should be studied separately (Jones and Yoshino 1996).

The effect of El Niño on the South Asia Monsoon is well understood. El Niño events introduce positive sea surface temperature (SST) anomalies, which weaken the Walker circulation and the circulation between South Asia and northern Africa. The SST anomalies also induce colder tropospheric temperature over Eurasia and warmer tropospheric temperature over the Indian Ocean. The associated negative meridional gradient of the tropospheric temperature anomalies is consistent with the existence of the weak Asian summer monsoon (Chou 2003). Increased winter precipitation caused by altered land-sea meridional thermal contrast further leads to a weaker Monsoon in the next summer. In addition, the temperature increase in spring may affect the onset date of the East Asia Monsoon (Jones and Yoshino 1996). In comparison, the effect of La Niña, i.e. negative SST anomaly, is limited to the eastern margin of the Tibetan Plateau and may only explain 2% of temperature difference there (Yin et al. 2000).

Some researchers nevertheless suggest that the relationship between El Niño/Southern Oscillation and the Indian monsoon precipitation is weakened due to a modified Atlantic circulation pattern (Chang et al. 2000). These researchers suggest that the warmer Eurasian land surface in recent decades resulted in a wetter monsoon even in the presence of El Niño. Yet this cannot explain that in cold events the El Niño effects did not become stronger. Thus they suggest that both the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO) have been in a positive phase in recent decades, which causes the westerlies to turn northeastward and a jet stream to be strengthened when it reaches Central and Eastern Asia.

Due to topographic and distance factors, the climate systems have different influences on different parts of the plateau. There are also differences due to altitude and latitude, therefore the plateau can be divided into several zones with their particular climate features. The delineation of these parts of the plateau is shown in Figure 2.6.

Northern Tibet with a latitude above 33°, along with the western and southern part of Qinghai Province, is traditionally called Changtang by locals. A description of this area states that the temperature in summer is only a degree or two above freezing, but the daily and seasonal tempera-

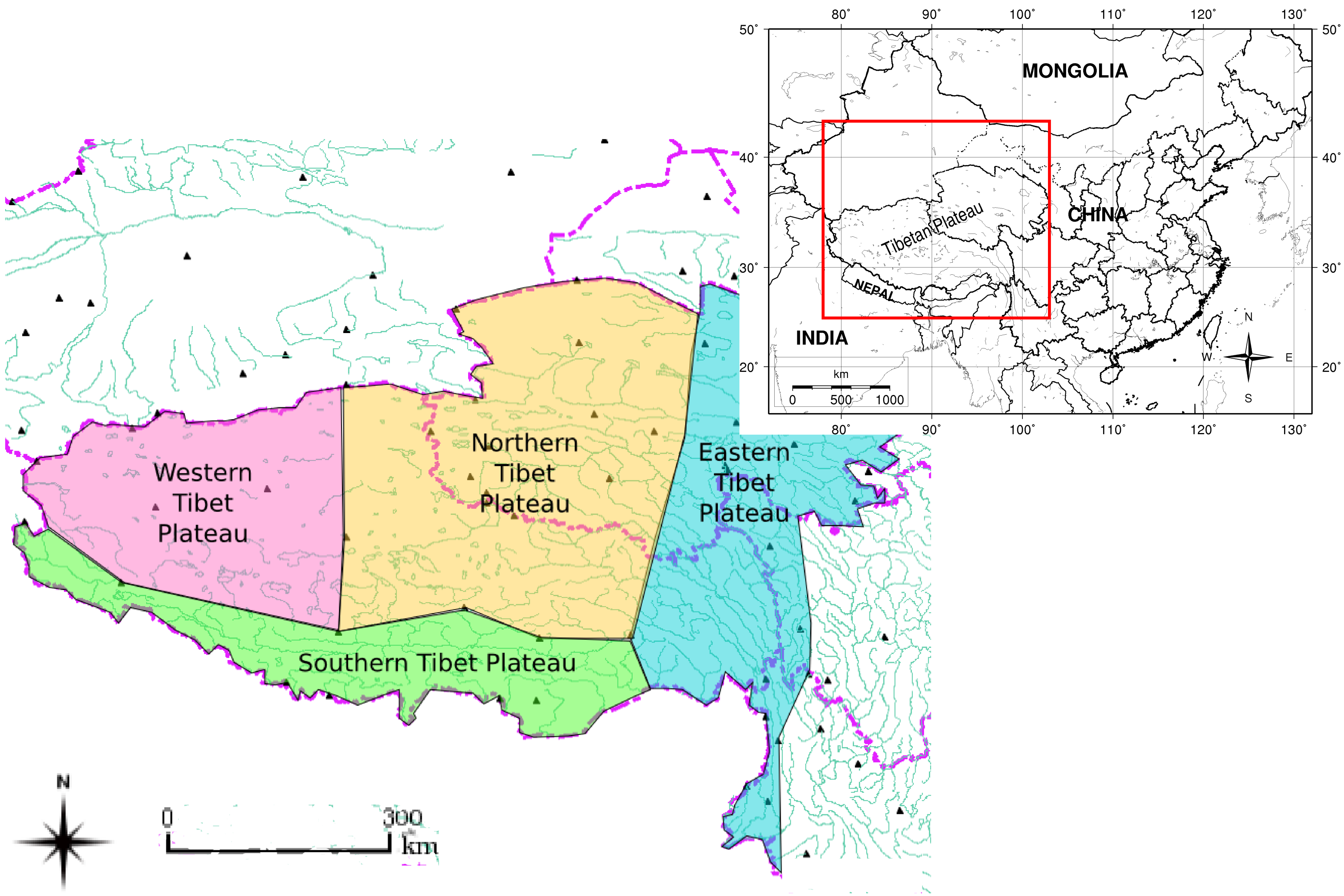


Figure 2.6: Delineation of Northern, Eastern, Southern and Western Tibetan Plateau. The base map was drawn using data provided by the National Fundamental Geographic Information System of China (State Bureau of Surveying and Mapping 2008).

ture ranges are much narrower than they are in many parts of the world. Temperature gradients are also low (Kingdon-Ward 1947).

This area is protected from monsoonal rainfall by the Himalaya mountain range to the south and the Hengduan Mountains to the southeast. Thus the precipitation can be as little as 25 mm per year. Not all precipitation is derived from moisture from the ocean. Precipitation in this area may have come from water vapour which has experienced several cycles of condensation-precipitation-evaporation under the monsoon circulation. Study and simulation show that over 58% of the precipitation comes from land surface evaporation (Yang et al. 2007). Due to lower temperatures, the evaporation of soil moisture in Northern Tibet is weaker than in the south, thus the precipitation is reduced (Yang et al. 2007).

In winter, the precipitation is mainly influenced by an India-Burma trough, an intensified subtropical westerly jet as well as ascending motion over the Tibetan Plateau. Other factors include moisture supply associated with the southerly flow over the Bay of Bengal and humidity over the Indian Ocean (Zhang et al. 2004).

The energy flux over the area shows significant diurnal and seasonal variations. In a given day the net radiation, sensible heat, latent heat, and soil heat flux increase with increasing solar altitude angle, and reach a maximum around noon. The sensible and latent heat fluxes vary with each month. From the beginning of July until September the latent heat flux is the main aspect; then sensible heat flux is the main aspect until the next May (Ma and Ma 2006). Such variations may have an effect on land-atmosphere interactions and weather events such as precipitation and wind.

The NAO is reported to have effects on the summer precipitation over the eastern Tibetan Plateau. The upper stream zonal flow variation associated with the NAO pattern is thought to be the major mechanism linking the regional precipitation fluctuation to macroscale circulation conditions (Liu and Yin 2001). During summers with low NAO index values, the westerly winds between 40° and 50°N from the eastern Atlantic to Europe are intensified, which generates anomalous anticyclonic flows in the lower-latitude area to the west of the plateau and stronger dynamic bifurcation flows to the south of the plateau, which promote development of cyclonic flows to the east of the plateau. In this case the southerly wind in the southern part of the eastern Tibetan plateau and the northerly wind in the northern part are strengthened simultaneously, which brings stronger precipitation in summer.

The topography of the area is dominated by several mountain ranges, including the Hengduan Mountains and Gongkar Mountain, in north-south direction, with deep valleys between them. As a result, a strong vertical gradient of vegetation is manifested in this area. The average altitude difference may be more than 1,000 metres. The climate type ranges from subtropical to alpine.

The northeastern part of the plateau has lower mean temperatures in winter than the southern and eastern parts. The warming from January to July is more intense over this area. The temperature in this area may be also related to Indian summer monsoon rainfall (ISMR) with a significant negative correlation between January precipitation and ISMR. But the correlation reduces rapidly through to December (Bansod et al. 2003). Another factor influencing winter temperature is climate change. Gou et al. (2007) concluded that the mean winter half-year minimum temperature increased by about 2.5 °C from 1940 to 1990. Meteorological data and partial correlation analysis showed that the eastern Tibetan Plateau as a heat source may influence the rainfall in the upper-middle reaches of the Yangtze river, with stronger heat sources cause abundant rainfall (Jian et al. 2006).

The southern Tibetan Plateau is mainly influenced by the South Asia Monsoon in the summer (Chang 1981). The monsoon brings precipitation and energy which is needed by vegetation during the growing season, which makes it possible to support the complicated ecosystem in the area. However, the influence of the monsoon is considerably reduced as it advance further into the north.

The glaciers in this area reflect the impact of climate change. They are influenced by the southwest monsoon in the summer, which can be seen as a part of the Indian monsoon system, and the westerlies in the winter. Intensified summer monsoon brings moisture that condenses at high altitudes and helps glacier growth, but increased temperature may hinder the advance of glaciers (He et al. 2003). As monsoons are weakened, and the glaciers are retreating, the precipitation is probably more important in the growth of glaciers. The complicated interaction between monsoon and glaciers requires more investigation in order to quantify the influence of temperature and precipitation changes.

The western part of the plateau is called a dry region. The moisture over the area is thought to come mainly from the Arabian Sea (Bao et al. 2003). The evaporation level is usually 20 to 50 times that of the precipitation. Precipitation is less than 50 mm/year, which falls in summer as convective rain or snow. Mean annual temperature has been estimated at -6.5 °C, with a monthly mean temperature maximum in July (11.9 °C and minimum in January (-15.8 °C). Evapotranspiration is estimated at 1,600 mm/year (Van Campo and Gasse 1993).

On the western Tibetan Plateau, atmospheric heating mainly results from vertical convection derived by surface heating (Bao et al. 2003). Sensible heat flux is dominant. Latent heat flux strongly depends on the existence of precipitation because when the soil moisture is increased the evaporation from the ground surface becomes active. Radiation flux also depends on the existence of precipitation, as the evaporation is linked to precipitation and controls the rise of ground surface temperature (Haginoya 2001).

The impact of climate change on the Plateau since the 1900s is complicated. Although at the moment it is not possible to list exhaustively all possible effects, some impacts of recent climate change can be examined. The most direct one is the change of temperature. Analysis of meteorological data shows that the temperature over the plateau is generally increasing, however, the degree varies with the location. The increase seems to be more apparent in the higher elevation of northern and western Tibet, and smaller in lower elevation areas and river valleys in the south (Liu, Guo and Wang 2008). In terms of precipitation, southern and eastern Tibet has seen precipitation reduced due to a weakened monsoon; some researchers report that precipitation increased in northern Tibet (Zhu et al. 2001), but it was pointed out that the increased precipitation is in winter and early spring in the form of snowfall (Chen et al. 2006), which thus cannot help the growth of vegetation but hinders germinating, although the water from snowmelt can be stored in the soil and used by the vegetation (Ose 1996). The low soil temperature caused by melting snow reduces the germinating rate of certain species, restrains the growth and development of grass and shortens the growth season by delaying germination (Liu, Dong, Z.-P. and Wei 2008, Gugerli et al. 2003).

Ye et al. (2008) reports that despite increased precipitation in some areas, the rise in temperature cancels out additional snowfall and accelerated glacier retreat as it increases evaporation. Yao et al. (2007) suggests that river runoff supplied by glaciers has increased by 5.5% compared to the 1980s, possibly due to increased rate of glacier melting. In some areas with large glacier cover the rapid retreat of glacier has also caused the rise of lake water levels, submerging villages and grasslands. Permafrost layers are similarly influenced. The altitudinal lower limit of permafrost area has risen by 25 m in northern Tibet from 1971 to 2001 and by 50 to 80 m in southern Tibet from 1981 to 2001. The average thickness of the active layer, which is subject to freeze-thaw interactions, increased by 0.15 to 0.50 m from 1996 to 2001. The ground temperature also increased by 0.1 to 0.3 °C during the same period (Cheng and Wu 2007). The freeze-thaw interaction has intensified in recent years, which leads to stronger heat exchange between the atmosphere and the ground and influences local climate. The degradation of permafrost also has a negative effect on the groundwater level and leads to soil degradation and shrinking of lakes. The degradation of soil is especially pronounced on meadow soil (Wang, Wang, Li and Cheng 2007).

An analysis of the last 40 years' observed climate data reveals that the southeastern part of Tibetan Plateau has become warmer and wetter, and the middle of the plateau gets less sunshine and milder wind and has also become warmer and wetter (Niu et al. 2004), while the northeastern part of the plateau has become warmer and drier. This implies deteriorating conditions for pastures in the northeastern Tibetan Plateau. The glaciers in the southern Tibet may also be in retreat due to increased minimum temperature through the year and may be able to provide less water to grassland in this area.

The monsoons, which are highly related to the differential heating of the Indian subcontinent and Tibetan Plateau, and Indian Ocean, are predicted by most global circulation models (GCMs) to decrease and bring less precipitation. It is estimated by Duan and Yao (2003) that for every 0.1 °C increase of northern hemisphere temperature, the 300-year accumulation trend of precipitation decreases by about 80 mm. The fact that a vast expanse of water exists as ice and snow in this area is an additional aspect of sensitivity to climate change (Sharma et al. 2000). It is also claimed that the global climate trend will lead to desiccation and increased drought in northern Tibet and Qinghai Province (Miller 1999*a*).

The Tibetan Plateau is a heat source in summer due to strengthened radiation, with the radiation energy absorbed by the plateau transported to a great height (Chang 1971). The elevated heating on the plateau may cause the early onset of the Asian monsoon and create a favourable circulation background for the monsoon onset over South China Sea (Ye and Wu 1998).

2.2 Pastoral history

2.2.1 Early human colonisation

According to Brantingham et al. (2003), the human colonisation of the plateau may date back to 40 kyr BP, and likely coincided with some large-scale changes in palaeoclimate. It is suggested that the early Upper Palaeolithic hunter-gatherer groups may first have entered the desert region around the plateau, at an altitude of about 3,000 m when lakes were at their highest levels in late Pleistocene (Brantingham et al. 2003, Aldenderfer and Yinong 2004). The steppe at this time supported a large number of wild ungulates, providing food source (Brantingham et al. 2003). As food and resources are evenly distributed in the area, the early colonisers were able to move to another location in a “random-walk” manner when resources are locally depleted (Brantingham et al. 2003). By such movement patterns they may have colonised the altitude between 3,000 and 4,000 m by chance at around 25 kyr BP. During the LGM, the lakes started to retreat and steppes were replaced by desert, leaving only patches of steppes around water sources. The increasing distance between patches rendered the “random-walk” strategy no longer tenable. The hunter-gatherer groups, therefore, had to adopt one of the two strategies: (a) to increase the breadth of resources to include lower rank resources such as small, fast game and plant resources; and (b) to abandon the random-walk and plan movements based on seasonal resource availability (Brantingham et al. 2003). It is not clear whether early hunter-gatherer groups survived the LGM on the plateau, but some of them may have moved up the plateau during the LGM as there was more precipitation available on the plateau than the surrounding basins which are in the rain shadow of the plateau. After the LGM the humans had to adopt a structured movement strategy according to seasonal resource availability due to the patchiness of resource distribution (Brantingham et al. 2003). The amelioration of climate created niches in the central plateau, especially in river valleys. The southeastern and northeastern corner of the plateau experienced expansion of forests, suggesting low-land flora and fauna may have adapted to high altitude and created more resource for early colonisers (Brantingham et al. 2003).

Full scale year-round occupation of the higher altitude Tibetan Plateau may not have happened until 15 to 10 kyr BP (Brantingham et al. 2003, Aldenderfer and Yinong 2004), or even until 8,200 years BP (Brantingham and Xing 2006), with the colonisers after this time thought to be fast in occupying the northern and western Tibetan Plateau. Microlith tools excavated from northern and central Changtang led archaeologists to speculate that foragers in the north of the plateau may have devised and utilised more effective tools in a highly variable environment and focused on large game-hunting, while in the south the environment was more benign and tools were cheaper and easier to make but not as effective (Aldenderfer and Yinong 2004). In some Neolithic culture sites dating back to 6 to 4 kyr BP, the reconstruction of the site resembles certain kinds of Tibetan architectures today; ceramics, stone tools and decorative items were found. These excavations suggest that residents on the plateau lived by a mix of hunting, gathering and plant cultivation. It is worth noting that most of the sites are located in the southern and eastern edge of the plateau. In a site near Lhasa which dates back to as early as 3,750 years BP, there is evidence of domesticated yak, sheep and pig (Aldenderfer and Yinong 2004). Due to the limited number of sites discovered and excavated, it is difficult to assert whether and how the agropastoralists in the southern and central Tibet moved to Changtang in the northern Tibetan Plateau.

The Tibetan polities since there were historical records and before Tibet became a nation state were probably small-scale, chiefly society scattered in the river valleys of the drainage of Yarlung Tsangpo river and its tributaries. The area is known today as Ü-Tsang. The livelihood in these polities were based on the domesticated animals introduced in the Neolithic in addition to horse, goat, iron tools, and sophisticated agriculture technologies. There was also evidence of other polities in Changtang and western Tibet (Aldenderfer and Yinong 2004). But it is not clear what their main livelihoods were and how they adapted to the harsher climate and higher altitude. It is also in question whether these polities are the result of development of Neolithic hunter-gatherer groups or have established by people emigrating from lower agropastoral areas in the south.

2.2.2 Traditional pastoralism

It was said that in 641 AD Princess Wen Cheng from China's Tang Dynasty brought the use of butter, tea, cheese, barley, beer, medical knowledge and astrology to Tibet (Grunfeld 1996). If this statement is true, it can be asserted that the pastoralism that can be observed today must originate at least from this time period. Before 641 AD pastoralism may have existed in Tibet, but given that butter is important for human survival in high-altitude areas, before it was introduced the pastoralism must have been fundamentally different from that after 641 AD. The production of dairy products may have been limited due to difficulty in storage. The grazing area may also have been limited to lower altitudes.

Pastoral practices are similar across the plateau, although the size and composition of the herds are varied. Despite being passed down through centuries and diffused all over the plateau, the essence of pastoralism seems little changed. In a typical Tibetan nomad family, men are the household heads and deal with important family affairs. They are responsible for grazing sheep and goat, transporting animals, moving tents, trading, and fighting. Women's main tasks include milking yaks, cooking, butter churning, fuel collecting, wool spinning and weaving (Yan et al. n.d.).

Figure 2.7: A herdsman bringing his sheep back from grazing. Photo taken by Zhen Wu, Tsinghua University Students' Mountaineering Club, in Anduo County, northern TAR, July 2005.

Milking is carried out at least twice a day. The morning milking is done early before sunrise, and may take more than two hours for large herds. Some of the milk is immediately consumed in meals, the rest is used to make butter and yogurt. All such work is done by women. They are also responsible for taking care of the young and the old (Tsinghua University Tecsun Students' Exploration Team 2006). Meal times are not fixed

Figure 2.8: Tibetan women milking sheep after they return from grazing. Photo taken by Zhen Wu, Tsinghua University Students' Mountaineering Club, in Anduo County, northern TAR, July 2005.

and women in a traditional family must invest a large proportion of time in cooking. They are also responsible for general housework and taking care of livestock at home. The dung of yaks, which is important as fuel in northern Tibet, is collected by women and dried for storage. Tibetan women who live in lower altitude areas may collect firewood instead of dung. Many Tibetan families keep dogs at home as guard dogs and to help with managing the herd.

Men go out to graze sheep in the morning, but usually set off much later than women do. They drive the herd along a certain path to the pasture, stay there for a few hours, then come back home about two hours before sunset. After they return home they generally do not help women with milking or other work. In the daytime, yaks scatter around the tent or house to graze, and come back to a shelter surrounded by short walls during the night (Tsinghua University Tecsun Students' Exploration Team 2006). This kind of practice is common in most of the pastoral Tibet, and has been observed by various scholars in their field studies (e.g. Miller

1999*b*, Goldstein et al. 1990, Næss et al. 2004).

Even if the story of Princess Wen Cheng is not considered true, the Tibetan people have led nomadic lives similar to what we see today since at least the 8th century. They have used the rangeland for migratory grazing, in which a tribe or a group of herders constitute a unit, and have used different types of rangeland during different seasons (Gyamtsho and Ismail 2006). Animal husbandry on the northern Tibetan Plateau is based on effectively exploiting the single, short growing season during which both frost and dry, high-velocity winds are common (Goldstein et al. 1990). While some early green foliage may appear on wet meadows and riverbanks, the majority of plant communities depend on monsoonal precipitation and begin to play a role in livestock forage in late May or early June. The growing season ends in September. But in the eastern and southern areas, the growth season is longer, supporting plantation of wheat and other crops.

Livestock in northern Tibet usually have two kinds of pastures for grazing. One is the summer pastures, located in higher areas, and grazed usually from April to September; the other is the winter pastures in the valleys, and grazed in colder months (Tashi et al. 2005). The winter pastures are grazed in winter and spring, and are preserved at other times of the year. For families with sedentary housing, winter pastures are often where their houses are located. Generally, pasture and crop residues for livestock tend to be adequate in late summer and early autumn but are in short supply in late winter and early spring. The energy and protein may be the major nutrients limiting livestock productivity in the latter seasons.

In some regions on the plateau, heavy snowfall in winter may form a cover which prevents domesticated animals from grazing. If the temperature suddenly drops, snow cover always changes into ice cover on rangelands and many animals inevitably die from lack of food. Snowstorms can also cause starvation and more deaths in the spring as animals are weak after a long winter and the germination of grass is delayed (Wu and Yan 2002). Therefore, it is of paramount importance to ensure food supply for animals during the winter. Aside from migrating between pastures, hay making is also conducted by herders to provide livestock with an additional source of energy. This is done by reserving a patch of grass in the winter pasture. However, the hay is only supplied to needy animals such as the young or weak ones (Manderscheid 2001). During winter, trading trips to nearby towns and villages may also be taken (Ewing 2002).

This seasonal grazing system, however, applies to sheep and goats only. Yaks are moved according to a different sequence. In some areas male yaks are left unsupervised in mountains throughout the year until they are needed for transportation. Female yaks are herded daily and moved with the sheep and goats to the autumn pasture. Although when sheep and goats return to home on winter pastures in December, the female yaks are normally moved to other ungrazed winter pastures (Goldstein et al. 1990).

Tibetan nomads tend to have the same kinds of animals in their herd: yaks, sheep, goats, horses, and *dzo*, the hybrid of yak and cattle, though the proportion of each kind varies from area to area (Miller 1999*b*), which may be due to climatic conditions and economic considerations. Climatic reasons may completely prevent the *dzo* from being present in northern Tibetan (Tashi et al. 2005). The rationale to have multiple species in the herd is manifold: the use of rangeland vegetation can be maximised; the nomads need products from various kinds of animals to meet the need of subsistence and family economies; the diversity of the herd can reduce the risk of animal loss in unpredicted situations (Miller 1999*b*).

The yak is native to the high altitude areas of the Qinghai-Tibet plateau and is the only bovine species that can fully utilise alpine rangeland resources (Weikai et al. n.d.). As yaks make life possible for humans in one of the world's harshest environments, Tibetan nomads place so much value on them that the Tibetan term for yaks, *nor*, is also translated as "wealth". Aside from providing a range of products, yaks can also be used as beasts of burden (Miller 1999*b*).

Sheep and goats can also be seen across almost the whole of the Tibetan Plateau. Although sheep and goats require more care than yaks, they can deliver handsome economic returns where it is practical to raise them (Weikai et al. n.d.). They give birth every year and thus are important for restocking after heavy losses during severe winters. Although horses are kept, they generally only make up a small portion in Tibetan nomads' herds because they graze untended and are subject to predation by wolves (Næss et al. 2004). They are usually used for transportation.

The sex and age composition of a herd reflects the pastoralists' intention, who allocates different "tasks" to the animals (Næss et al. 2004). The Tibetan nomads tend to have a relatively large number of male sheep and goat compared to sedentary and modern practices in the herd, which is considered as "irrational" by non-pastoralists from a Western view. However, the rationale behind this is the need for protein and fat (Miller 1999*b*). As about 20 sheep or goats have to be slaughtered for a nomad family's food every year, and some more are traded for commodities that are useful but cannot be obtained by other means, it would be more economic to slaughter and sell male ones than female ones. The nomads, however, do not seem to control the sex ratio in their herds deliberately but let them follow a natural course, thus the sex ratio is expected to be close to 1:1.

The size of a herd is usually encouraged to increase whenever possible. Aside from the common perception that Tibetan nomads consider the size of herd as a symbol of wealth and status, a larger herd provides a kind of insurance in the face of unpredictable disasters, because the larger herd can have more individuals survive and thus can recover quickly. Even so, significant fluctuation of herd size occurs after disasters such as snowfall (Næss et al. 2004). For example, between 1955 and 1990 six severe winters were reported in Tibet and each caused 20 to 30% livestock loss (Sheehy, Miller and Johnson 2006). Miller (1999*b*) suggested that 25 sheep, or 5 yaks per person is the minimum number of livestock required to avoid poverty. Nomads with a herd smaller than this will not be able to secure their livelihood. In a pastoral system characterised by high mortality (Miller 1999*b*), a large herd is necessary to ensure survival of the herd and the nomad household.

The pastoral economy in Tibet in the period before 1959, when the Chinese government established its direct control of the area, was largely focused on subsistence, similar to other pastoral regions around the world (Manderscheidt et al. 2004). Livestock products provided food, clothing and shelter, and through trade, provided other products such as tea, grain, and ironware to the nomads (Næss et al. 2004).

The subsistence demands of Tibetan nomads and agropastoralists are met by utilising products from various animals and bartering with these products. Yaks provide multiple products which are most closely related to Tibetan nomads' lives and production activities. Yak's milk is too oily to drink directly but can be made into butter through churning. Dried yak beef is the major food supply when the pastoralists are away from home or on the route of migration. The yaks' coarse belly hair is spun and woven into tent material. The finer wool, or *kullu*, is used to make ropes and blankets. Traditionally, the hides of the yaks were used to make soles of boots and shoes (Weikai et al. n.d.). In the Changtang area where firewood is not available, the dung of yak is the exclusive source of fuel. Thus the yak is an irreplaceable kind of animal on the plateau.

Though the yak is considered to be the characteristic animal of Tibetan pastoralism, sheep and goats are more important economically. Both of them produce milk, meat, wool and skins. Goats produce more milk than sheep and for a longer time of the year. The products from livestock are basically sufficient for a pastoral family's subsistence, given an adequate number of livestock. If there are surplus products such as yogurt or dried beef, pastoralists usually use them in barter for tea, grain and salt imported from outside the plateau or the southern, milder part of the plateau.

Local communities have learnt to adjust to the harsh environment, defined by high altitude above 4,000 m, low annual mean temperature around 0 °C and relatively low rainfall (Bauer 2005), as their highly risky pastoral production has persisted for thousands of years. They have developed mechanisms for mobile livestock grazing, selection and improvement for livelihood security. But such indigenous knowledge generally has not been recorded and is easily ignored by experts and administrators (Yan 2004).

The traditional pastoral system since the 7th or 8th century was organised around communities. With low population and livestock density, the system has been able to retain its mobility and flexibility in adapting to the harsh environment. The rangeland belongs to tribes and has distinctive natural boundaries, such as ridges and rivers. Within the tribe, the pastures are reallocated to subtribes every spring with little consideration on number of livestock (Yan et al. n.d.). The allocation is usually determined by the leader of the tribe, but for tribes serving a certain feudal lord, the lord would be in charge of allocating plots of pasture to individual households (Goldstein et al. 1990). The pastures are not fenced but boundaries are enforced. Nomad households can only use their assigned pastures.

Each pasture was considered suitable for a fixed number of animals calculated on the basis of a unit locally called *marke*. How these stocking ratios were determined was not clear, but they were not frequently adjusted (Goldstein et al. 1990). The allocation of pastures was adjusted every few years according to the changes to the size of herd in each household.

It is commonly accepted in China that Tibetan nomads wandered freely across the grasslands with no permanent home and without any management of the grazing lands. In fact, the Tibetan pastoral system was designed around the movement of livestock to different pastures at different seasons of the year and the tracking of favourable forage conditions. It also included a relatively stable relationship between pastoralists and rangelands. The family or group leaders of pastoralists make decisions on herd movement taking into account past use, snowfall and rainfall, growth state of grass, and condition of the animals (Miller 1999*b*). The nomads' movements were thus well prescribed and are highly regulated (Miller 1999*a*).

Officials, who are not usually pastoralists themselves, tend to impute widespread rangeland degradation to herders and their overuse of rangelands, but research shows that aside from changes related to climate trends, the most fundamental cause has been inappropriate government policies relating to the pastoral areas due to insufficient understanding of the rangeland ecosystem (Yan 2004).

2.2.3 Changes and developments of pastoralism in the 20th century

After they managed to overthrow the Kuomingtang (Nationalists Party) government in Nanjing, which ruled mainland China from 1911 to 1949, the People's Liberation Army marched on towards the western and southern provinces including Yunnan, Hainan and Tibet to eliminate the remaining Kuomingtang forces. After a few failed attempts to resist the Chinese Army and a suspended appeal in the United Nations General Assembly, in April 1951 a Tibetan delegation began negotiations with the Chinese government and reached a 17-Point Agreement on the Peaceful Liberation of Tibet on 23 May of that year (Richardson 1962). The agreement claims that the Chinese People's Government shall assist all national minorities to develop their political, economic, cultural and educational construction work. The main content of the agreement included recognising the Tibetan People's right of exercising regional autonomy, not altering the existing political and religion system, and developing agriculture, livestock-raising, industry and commerce and improving people's livelihood "step by step". It was also mentioned by Richardson (1962) that an immigration of 40,000 families of Chinese farmers into Tibet was announced, but there is no evidence in other sources.

There were attempts by the Chinese to change the Tibetan political system despite the 17-Point Agreement, but they were held back or put off (Richardson 1962). But the economic problem was worrying. The food supply to Chinese soldiers was very limited due to the difficulties in transportation. The United States boycotted wool from "communist" Tibet. Beijing's response was to purchase Tibetan wool at three times the market price (Grunfeld 1996). Another unexpected problem was inflation because of money brought in from inner China and distributed to the peasantry in the form of grants and loans. In order to deal with rising food prices, the People's Liberation Army (PLA) established their own farms on unused land, causing resentment among peasants who were not allowed to do so. Food imports doubled in the period 1954 to 1957 and inflation was not controlled until later in the decade.

The land allocation and management system on the plateau was relatively stable since the establishment of the lama/aristocrat politics system in Tibet by Mongolian rulers in 13th century. The family- or clan-based system had always been the major feature of land management in

Tibet. However, this system has undergone fundamental changes in the 20th century, which transformed the system into a semi-democratic program in a subsistence-to-market transition background, by changing the way of land management and allocation from monastry/feudal ruler dominated to state planned. The major events in the transition of land management systems include the “democratic reform”, Grain First and the Great Leap Forward campaigns in 1950s, collectivisation in 1960s through 1970s, Open and Reform in 1980s and privatisation since the late 1990s.

The Grain-First campaign which began in the 1950s in other parts of China was considered to have the most negative impact on the environment. In this movement, even land unsuited to agriculture was reclaimed to satisfy the country’s grain need (Ho 2003). In this process many pastures which could not support grain and vegetable productions were converted to such use, causing damage to the grassland ecology with virtually no increase in food production. This movement ended following the 1961 nation-scale famine, which was caused by national-scale ecological disasters and the Soviet Union’s sanctions due to border disputes in Northeastern China, but the idea that agriculture is critical for people’s lives and national security still remained and continued to encourage rangeland transformation in later years.

Transportation also changed the characteristics of the plateau and facilitated further transformation. From 1955 to 1959, networks of transportation and communications were established in Tibet. The Qinghai-Tibet highway was extended from Lhasa to Shigatse in 1955. By April 1956 more than 4,300 km of motor-roads were open to traffic. The Sichuan-Tibet highway north section was completed in October 1956. Airfields were also completed during this period, including one in Lhasa completed in 1956, another in Tingri, about 40 miles north from Mount Qomolangma (Mount Everest), in 1959 (Ginsburgs and Mathos 1960). These construction projects brought considerable impact to Tibet. The import of goods from inner China had a manifold increase. In return, the State's purchases of animal products and other local merchandise was announced to be ten times greater than before the roads were built.

Reform policies for nomadic life proposed as the Communist Party's official view stated that "a nomadic life is neither beneficial to the development of animal husbandry, nor to the prosperity of the human population"(Grunfeld 1996, p.125). The introduction of veterinarian stations, experimental breeding stations, schools, and fixed winter feed areas led to a marked decline of mobility. The forced confiscation of weapons also affected nomads' life and their attitude towards the Chinese government (Grunfeld 1996).

These policies, Grunfeld comments, were not able to change the rigid and ossified feudal society in Tibet. Many of them had implications deeper than can be observed. Misunderstandings of Tibetan Society, in addition to persistent Chinese chauvinism, and an inability to respond to the Tibetan people's resentment, were the greatest barriers to the Chinese governance in Tibet.

In this period, financial aid was applied for and utilised by Tibetan cattle-breeders. The State purchase price was high and stable. Courses on stock-raising were also given to herders. After the riot of Tibetan residents caused by the exile of Dalai Lama in March 1959, the Chinese government began the implementation of "democratic reforms" in Tibet comprising land redistribution and the abolition of serfdom. But in pastoral areas these measures were relatively less implemented (Ginsburgs and Mathos 1960). These measures may have directed pastoral products to inner China and merchandise to Tibetan pastoralists, but did not profoundly change the customs of Tibetan nomads because their management system mostly remained unchanged.

Though the large-scale collectivisation movement marked by the establishment of communes started in eastern and central China as early as 1957 (Johnson 1988), Tibet was not involved until a few years later, as the government decided to collectivise it gradually. In 1961 the relatively mild policy called mutual aid (*rogre*) was introduced to Tibet. Houses from middle and poor classes were formed into mutual aid groups consisting of several households that jointly held pastures and corporately carried out tasks such as herding (Goldstein and Beall 1989). Economic decisions and the resulting income or loss still remained the discretion of individual households.

Rich nomads at this time were not permitted to join the mutual aid groups, and had to pay higher taxes and wages. But they were permitted to retain their animals and continue to hire poor nomads as servants and shepherds, though such practice was forbidden in other parts of China (Goldstein and Beall 1989).

In 1962 the commune system was reformed to avoid economic catastrophes and objections from people. The commune system eventually adopted in Tibet was not like that of 1958 in inner China. The two-layer organisation of commune and production team based on administrative and natural villages apparently led to better relationships and efficiency, though such organisation was not practised over the whole of Chinese Tibet (Dreyer 2003). However, the commune still had all livestock and pasture in its control. People were forced to turn over the livestock and most of their property to the collective by shares (Yan et al. n.d.). The nomads thus had to work for the commune to obtain "work points", cash and provisions for their families (Goldstein and Beall 1989). The basic accounting unit, as in other areas of the country, was the production team. Livestock owned by collectives, or communes, were usually divided into different groups. Labour forces on the farm were also accordingly divided into different groups (Yan et al. n.d.).

In the 1970s, the formation of communes was accompanied by large-scale efforts at crop diversification. In 1973 – 1975, successive delegations of scientists from inner China investigated the area's climate and terrain to ascertain what sort of crops and animals could survive high altitudes. As a result, species such as winter wheat and hogs were introduced, or their population enlarged. A wide variety of fruits and vegetables were also introduced. Though good harvests were reported in the first few years since the practice, such practice led to an ecological disaster in late 1970s, in which large areas of pastoral grassland were lost without any crop production in return because the poor nutrient state of the soil and short growth season with unpredictable weather patterns cannot support long-term agriculture (Dreyer 2003).

In May 1980, Party Secretary Yaobang Hu and Vice-Premier Li Wan made an unprecedented fact-finding visit to Tibet to see conditions there. Hu later announced a reform programme for Tibet, which include reducing the burden of the masses, revising policies to suit the local situation, developing Tibetan culture, education and science, and regulating the proportion of Tibetan cadres in government functionaries within the next 2 – 3 years (Goldstein 1997). As a part of the programme the commune system should be changed.

From 1981, the "Household Responsibility Programme", which was started in the crop production sector in Anhui province, was introduced to the Tibetan pastoral system (Miller 1999*a*). The idea of the programme was to give the incentive to increase production back to farmers, who would not work to their best in the commune system where everyone is paid the same for any given time of work. The commune system thus was replaced. In many areas livestock once owned by the communes were distributed equally among the constituent households. The pastures were also assigned to groups organised in a similar way to communes. All rangelands continue to be owned by the state or by collectives. Policy also prescribed the derivation of stocking rates for household pastures to deter overstocking (Banks et al. 2003).

The fact that livestock were privately owned by nomads, while the pastures were shared among the group members who did not own property rights of land, raised the government's concern that nomads may want to maximise their short term interest at the cost of the environment, especially after grassland degradation had been demonstrated in some areas (Ning and Richard 1999). To avoid the so called "tragedy of the commons" (Hardin 1968), the Household Land Contract Programme was introduced in the 1990s (Sheehy, Thorpe and Kirychuk 2006), which was in effect privatisation of land use rights. Under this programme, the pastures are leased to nomads under a long-term contract, which is often valid for 30 or 50 years. This is based on the assumption that nomads will be more responsible for the land on which they graze their herds if they have long-term right of use of it. At the same time, the government wished to restructure pastoral production in Tibet by changing the traditional system. The aims include (Ning and Richard 1999):

- Increase livestock off-take and pastoral incomes through more intensive management, such as sedentarisation and fencing;
- Raise the nomads' enthusiasm for rangeland management through privatisation of rangelands;
- Rationalise land use by limiting livestock numbers; and
- Increase the nomads' level of knowledge and skills and strengthen their marketing sense through improvement of infrastructure.

By the end of 2003 about 70 percent of China's usable rangeland was leased through long-term contract of use, of which 68 percent was contracted to individual households and the rest to groups of households or to villages (Yan et al. 2005).

In recent decades, nomads across most of the pastoral areas of the Tibetan Plateau have built houses for themselves and shelters for their livestock, usually in the traditional winter-spring pastures where they may spend up to 6 – 7 months of the year (Miller 1999*b*). Nomads are also increasingly fencing pastures to reserve grass for winter and spring grazing and are planting tame pastures for either winter-spring grazing or for hay (Miller 1999*b*). Such practices are encouraged by the government. Winter or year-round pastures are allocated and fenced. The pastoralists are asked to build a permanent house, a barn, and a shelter on the pasture. This is called "the three self-contain construction". In some counties nomads are subsidised by the government for such projects. Artificial pastures and exclusive hay pastures have also been established in some areas where natural pastures are degraded.

Figure 2.9: Houses built for a group of semi-sedentary pastoralists near the town of Amduo in northern Tibet. Photo by Zhen Wu.

It is believed that sedentarisation will help the pastoralists improve production through intense rangeland management and more convenient access to veterinary services. The pastoralists' households can also have access to schools, hospitals, and infrastructures such as road and electricity, which is much more difficult to provide when they are leading a nomadic life.

The elements of the natural environment examined in this chapter determine the mode of pastoral life in Tibet. Although pastoral life has undergone changes in institutions, land ownership and economic systems in the 20th century, and possibly throughout its history, the core value of balancing the level of resource requirement has not changed. Any new approach to maintaining the existing way of life must also address this core value. The meteorological system of the Tibetan Plateau determines that the weather in this area is subject to the influence of various weather systems and frequent annual changes. The weather systems in return are influenced by trends of climate change. These factors imply that the resilience study of the area must pay attention to the functions provided by vegetation, which is the base of the economy and society and is susceptible to natural and human disturbances.

Chapter 3

Theoretical and methodological background review

The ecosystem resilience approach is used in the study to compare the sustainability and adaptability of Tibet's nomadic pastoralism and modern livestock management. This chapter reviews the invention and development of the resilience concept, as well as its applications. The latter part deals with remote sensing as a data collecting approach and how resilience assessment uses remotely sensed data.

3.1 Resilience

Resilience can have multiple levels of meaning (Carpenter et al. 2001). Although it has been used mainly as a metaphorical description of systems, now it is possible to define and illustrate a system's resilience using mathematical models and plots (e.g Moritz et al. 2005, Bolte et al. 2007), and conduct measurement and assessment given adequate understanding of the system in question and sufficient data (e.g Martin 2004), although the cases of actual measurement of resilience are limited in number. No matter whether the metaphorical, theoretical or practical level of resilience's meaning is concerned, in practice the first problem is defining the components and processes of interest as well as forces and disturbances that influence their properties. In other words, resilience *of* what *to* what (Carpenter et al. 2001) is the first question in resilience studies. Because both the system's properties and external forces change with the temporal, social and spatial scale at which observation is conducted, the definition of a system's resilience also needs to specify at which scale is the measurement and assessment conducted.

Compared to climax ecosystems such as forest ecosystem, the grassland ecosystem is transient and more likely to be influenced by environmental changes or species migrations. Human management of these ecosystems often focus on preventing the shift of states and loss of key components or functions. However, due to the complexity of ecological interactions, human management of transient ecosystems does not always achieve the goal. It is argued that trying to maintain an equilibrium in such a transient system is not feasible nor desirable. What is important is that the key functions or services the ecosystem provides should be preserved in the face of unavoidable changes. Thus the concept of resilience was proposed in 1970s, and since then widely applied in various geographical settings and management scenarios.

3.1.1 Ecological Resilience

Ecological resilience is measured by how much disturbance can be absorbed by a system before it is restructured with different variables and processes (Gunderson and Pritchard 2002). In the study of complicated ecological-socioeconomic systems, researchers are often challenged with the task of examining which kinds of disturbance may occur and how well can the system cope with these disturbances without changing its key structures and functions. Furthermore it is usually necessary to understand the degree to which the system is able to self-organise and build the capacity to learn and adapt (Carpenter et al. 2001). These questions are extremely difficult to answer well unless one obtains a comprehensive understanding of the system's various aspects, especially that of key processes and agents. Ecological resilience research is based on the same premise. It requires the researcher to identify the key component and the variables that may cause a sudden shift and alteration of such components. In return, resilience assessment can tell managers what factors are threatening the sustainability of the system by influencing what variables, allowing them to take corresponding action.

Another feature of ecological resilience is that it not only acknowledges the existence of multiple possible states of a system, but also points out that the transition of the system between different states may not be a linear process as many other models assume. The transition may be very non-linear and sudden, and therefore cannot be described with simple continuous function. Ecological resilience introduced concepts from nonlinear mathematics to solve such a problem. Moreover, ecological resilience does not rely on the assumption that systems are constantly in stable states. Instead, non-equilibrium and non-stable states are considered "normal" in its studies.

Resilience studies do not only focus on processes at a single scale. Instead, cross-scale processes are extensively studied in resilience research. First, this is because resilience at one spatial extent is often "subsidised" from a larger spatial scale, like a city supported by surrounding farms illustrates; Secondly, today's social system based on fossil fuels is subsidised from a process that takes place at a larger time scale; thirdly, resilience in ecosystems is determined by the integrity of functions provided by different species in the system, while these species operate at different time and space scales; some disturbance processes also have the ability to drive larger-scale changes by small-scale changes (Peterson et al. 1998). Cross-scale resilience is considered as a complement to within-scale resilience and it is a irreplaceable prerequisite of the system's self-organisation and sustainability.

Beside ecological resilience there is also another paradigm in studies of ecosystem's ability to recover from disturbances called engineering resilience. This concept assumes that a desirable, equilibrium and static state for a system always exists and resilience is measured by the time the system requires to return to the stable state from a given disturbance (Holling 1996*a*). In this study, whether equilibrium state exists for a grassland system is questionable. It is also difficult to define such a state if it does exist. Therefore ecological resilience is chosen over engineering resilience as the theoretical base of the study.

3.1.2 Adaptive cycles

From an ecological resilience perspective, a system does not tend toward some stable or equilibrium condition, but pass through four characteristic phases: rapid growth and exploitation (r), conservation (K), collapse or release ("creative destruction", or Ω), and renewal or reorganisation (α) (Carpenter et al. 2001).

A key feature of the metaphor is the existence of relatively brief periods during which major changes occur: Ω and α phases. In the Ω period the system dynamics rapidly collapse, followed by a major perturbation during which some components and attributes of the system may be lost. In the following period of reorganisation, the α phase, novelty can arise. In the following r phase, the system settles into a new trajectory in a well-defined basin of attraction. During the long, slow progress from r to K, there is a diminishing likelihood that new novelty will arise, although the system may become more complex as new connections are solidified. Resilience changes throughout the adaptive cycle, and different aspects of resilience are demonstrated at particular phases of the cycle.

It is useful to classify the four stages just as biologists classify life-cycle stages that recur in species after species. Managed systems show a tendency to repeat characteristic behavioural phases and it is useful to identify them because different management and policy interventions are appropriate in different phases (Walker et al. 2002).

From phase r to K the system is under strong control, and changes slowly. Regulatory policies and efforts to increase efficiency may be appropriate, although careful experimentation is sometimes critical. Applications of techniques such as optimal control can be useful. However, resilience can be lost through gradual changes in underlying slow variables. An example of r to K phase is the Early Dynastic Period in Ancient Mesopotamia (Redman and Kinzig 2003), in which a series of experiments in organising cities and their hinterlands were carried out. The temple ovals, palaces, and royal burials built in this period reflects the growth in social capital and connectedness, which is the feature of the r to K transition. The Sumerian city-states disappeared in this period. At the same time an ethnically distinct dynasty with the first Semitic rulers and a large administrative apparatus was established. This marks the completion of the transition. A more recent example is Western Australia in late 19th Century (Allison and Hobbs 2004). In the period labelled the "Move Forward", government policy drove development. Government institutions set out the concessions and conditions for obtaining farmland, enabled land-use planning and accelerated land release for agriculture. By the late 1920s, 50% of the areas now identified as Western Australia's agriculture region was cleared of native vegetation. This caused the rise of the water table at first, but the introduction of water demanding crops and irrigation systems caused salinisation and water shortage in downstream communities. These features are characteristic of the r to K phase.

From phase Ω to α the system changes rapidly. No equilibria, turbulent, or novelty can enter. The system is susceptible to loss of resources, and measures to conserve capital are appropriate. It is also vulnerable to entering a potentially undesirable configuration. Influential ideas can become entrenched and guide subsequent evolution of the system. For example, on the Causse Méjan, France, demographic pressure between 17th and 19th century led to an acceleration in land clearance and the temporary cultivation of cereal on poor rangelands, often resulting in accelerated erosion. By the late 19th century there was practically no forest on the Méjan. Rural emigration from 19th Century on made the Méjan and the surrounding area lose over 80% of its population, and much of its agriculture and textile industry (O'Rourke 2006). These changes can be regarded as the collapse of the old system, and innovation could not be introduced into the system due to extreme loss of resources. But the loss also made possible spaces for the reorganisation of the system.

Within one system there can be subsystems at different scales, each with its own adaptive cycle. The subsystems are semi-autonomous but cross-scale interactions do occur (Walker et al. 2002).

3.1.3 Slow variables

It has long been observed in ecosystems that processes at large scales often occur at a slower pace while small-scale interactions have a higher rate of occurrence. The large-scale processes are the collective result of many interactions at small scales thus the effect's distribution in the hierarchy takes longer to reach higher levels or larger scales. The characteristics of the large system are therefore reflected in some properties' slow change. On the other hand, the changes in large-scale systems may have few predictive signs and when they take place are sudden and dramatic, sometimes causing the system to "flip" to another state. It is believed that such "big effects from small causes" (Carpenter and Turner 2000, p.495) are the characteristic consequence of coupled slow-fast cycles in ecosystems. The essence of the phenomenon is that fast processes at smaller scales are changing some properties at larger scales, but only at a very slow rate so that changes are not easily observable.

These slowly changing properties often dictate the system's functions and behaviours at various scales. The variables that represent these properties thus reflect the fundamental changes of the system and serve as a measurement of the system's current state. In resilience studies slow variables determine the possibility that the system may shift to another state. Therefore if slow variables can be measured they can provide a measurement of resilience. However, slow variables take so long to have perceivable or significant change that in many ecological models they are often treated as parameters (Carpenter and Turner 2000). Direct measurement of changes of slow variables in many cases are impossible.

The characteristics of slow variables also make them carriers and stores of a system's memory throughout history. In times of disturbance and fluctuation, as long as the system's slow variables are persistent, the changes of fast variables and processes can always be reversed because the fundamental processes are still in place. It has been pointed out by several researchers that ecosystem management should focus on preserving "institutional memory" instead of dealing with syndromes and single variables (Olsson 2003, Folke et al. 2004). To do so is consistent with preserving key functions and structures by maintaining slow variables.

3.1.4 Assessment methods

In the study of resilience, a model of the system, or its processes and functions, is often a prerequisite and a necessary tool for further assessment. Models can help researchers identify the system's key components at the conception step of study, and can be used in the subsequent steps to simulate these key components and how they influence the system's resilience. In many cases, established ecological models can be used in resilience analysis and identification of ecosystem functions. However, as some of these models are based on the equilibrium assumption, some modification may be required before they can be adopted. Such modifications may involve adding bifurcation points in the model, or setting conditions where the linear assumption is no longer valid.

Scale is a defining character of resilience models, as it determines what phenomena to study or ignore, and the applicability of assessment results. Scale in resilience studies is defined as a series of spatial and range frequencies, which define a lower scale below which faster and smaller interactions are treated as noise and an upper scale above which slower and larger processes are treated as background (Peterson et al. 1998). Different from many ecosystem models, which assume the species and interactions exist on a uniform scale, resilience models attempt to address inter-scale processes, as Ludwig et al. (1978)'s budworm research shows, in which the link between bird predation of worms and the state of the forest is examined, showing that bird predation at local scale impacts the viability of forest at a larger scale (Peterson et al. 1998).

The modelling approach to studying resilience is usually implemented by studying key variables, such as phosphorus in lakes (Carpenter et al. 2001), or ecosystem interactions such as grass/shrub competition. It has been argued by resilience researchers that to represent ecosystem management, models should at least incorporate a social dimension in which agents assess the status of the system and possible future states, compare possible actions and choose policies that may alter the system and the scope of choices (Carpenter et al. 1999). The modelling of social interactions and policy-making process can be very complicated but suggests a possible direction to more sound socio-ecological system resilience modelling.

The measurements made in models are based on sizes of basins of attraction derived from quasi-steady state analyses. The size of the domain of attraction may be difficult or impossible to measure under field conditions. However, surrogate indicators can be defined that should change monotonically with resilience. Biophysical surrogates are often based on slowly changing variables. Socio-economic surrogates are related to the flexibility of agents to negotiate local solutions to the problem and the existence of incentives to increase resilience (Walker et al. 2002).

Carpenter et al. (2005) suggested using surrogates to measure resilience. The resilience of social-ecological systems can be indirectly inferred from these surrogates. However, the relationship between resilience and any particular surrogate may be dynamic, complex, and multidimensional. A suite of surrogates will be needed to represent the key features of resilience for the particular SES.

To determine suitable surrogates, firstly one should determine the central problem or the key component of the system, which leads to the identification of focal variables and conditions of interest; then the feedback processes among components of the system related to the central problem should be identified; knowing the goal and interactions, a system model can be formed, which serves as the base to identify resilience surrogates (Bennett et al. 2005). To ensure that the surrogates are consistent with the resilience of the SES, the following questions should be addressed before identifying surrogates (Carpenter et al. 2005):

- Are the surrogates consistent with resilience in modelling exercises?
- Are the surrogates consistent with long-term observations of the SES?
- Are the surrogates consistent in comparisons across SESs?
- In cases where SES have changed substantially, thereby revealing thresholds, were the surrogates consistent with the observed changes?

The approaches to developing surrogates may include:

- Stakeholder assessments;
- Model explorations;
- Historical profiling: history of the SES is assessed to classify more-or-less distinct dynamic regimes, and analyse events during the transitions;
- Case study comparison.

A question remains in this approach that whether surrogates can represent the resilience of the system, with sound statistical and ecological meanings. The applicability and comparability of surrogates for the same type of ecosystems in different temporal and spatial locations is also questionable.

Another paradigm in the measure of resilience is similar to the surrogate approach but with methodological difference is the identity approach suggested by Cumming et al. (2005). They argue that resilience is equated to the ability of the system to maintain its identity. The identity is expressed as a set of components and relationships and their continuity through space and time. To identify these components and relationships means one can parse the system into a series of elements, thus the problem can be transformed into measuring a few focal variables that reflect changes in identity. The result obtained is a measure of the system's likelihood of a change in identity under "clearly specified conditions, assumptions, drivers and perturbations" (Cumming et al. 2005, p.975). What variable to measure is a subjective choice, as Cumming et al. argued that it is impossible to examine all aspects of a complex system to gain understanding of all variables that may contribute to the system's identity. This does not mean the variables to measure are determined arbitrarily or prior to the study of the specific system, which may lead to a conclusion that largely depends on the choice of variables. Instead, the choice of variables is based on the definition of the identity of the system and essential attributes, ideally derived from stakeholder groups. Then critical thresholds of these variables beyond which the system will lose its identity will be determined. The next step is to estimate effects of internal and external drivers. Finally, a few alternative future scenarios are considered based on analysis above. This approach has been employed to study Amazon forest systems and the impact of a major highway project in this area (Cumming et al. 2005). The continuity of both ecosystem and social system were considered as the identity of the Amazon forest system. The key variables were forest clearing, hardwood seedling recruitment, and the level of traditional forest extractivism. The thresholds were identified accordingly. The drivers were road paving and a series of other policies. It was found that the beef price and demand for rubber, as well as seedling recruitment, would influence the identity of the system.

This approach is consistent with the definition of ecological resilience. However, its methodology has a few possible pitfalls. First of all, the identity of the system is determined by stakeholder groups, and thus may not address some underlying structure or components that are vital to the system's existence and may be prone to cause surprise in subsequent management. The estimation of probability of identity change is based on a linear measure of variables and the identification of thresholds does not consider combined cause and effect, while multiple, cross-scale interactions may be the real cause of loss of identity and resilience. Given these problems, the advantage of this approach is that complex and error-prone system modelling and search of slow variables are avoided. The focus group approach allows quick identification of key aspects. Therefore, this approach is suitable as the initial step of continual adaptive management.

The surrogates discussed above are direct measures of the system's properties. In comparison, resilience can also be assessed using surrogates that indirectly reflect the system's functional completeness. It has been argued that in many ecosystems only a few dominant species account for most of abundance. Many other minor species have similar functions to the dominants but respond to environmental changes differently. Therefore, in times of change when the dominant species decline or are lost, the minor species with similar functions can compensate the system's functional loss, thus contributing to the system's resilience (Walker et al. 1999). How these species are distributed in the system's function space thus becomes a measure of resilience. The first step of assessment involves identifying the functions of the system. Then the researcher examines each species' functions and summarises them in two possible ways: (a) the number of different function combinations in the community; and (b) the standard distance the species are apart in the function space. Due to different measurement units and limited understanding of ecosystems, the measures of functional attributes should be transformed into a normalised scale or score. The distance of two species can be calculated using a series of different distance definitions but usually in euclidean distance:

$$ED_{jk} = \left[\sum_{i=1}^{I} (A_{ij} - A_{ik})^2 \right]^{\frac{1}{2}} \tag{3.1}$$

where A_{ij} and A_{ik} are the attribute values of species j and k for attribute i, and I is the total number of attributes in question. In order to make the difference and similarity in function space easier to identify it is possible to omit the square root in Equation 3.1:

$$ED_{jk} = \left[\sum_{i=1}^{I}(A_{ij} - A_{ik})^2\right] \tag{3.2}$$

Combining the distances for all species pairs gives a matrix, whose sum can be used as an indicator of function diversity and redundancy for the system. The distance between species can be used in a cluster analysis to tell which species have similar functions. A further examination of species' response to disturbance reveals the system's resilience. A notable feature of this approach is that it does not require the explicit identification of slow variables, although at the price of demanding a response analysis for each species concerned to each possible disturbance or disaster. It is also prone to ignoring surprise events.

The understanding of grassland grazing has evolved from a model based on linear, reversible succession, through recognition of hysteresis effects in recovery to the development of multi-state models (Janssen et al. 2000). However, these state-transition models are hard to formulate in retractable forms. Perrings and Walker (1997) argue that the determinants of natural vegetation in state-transition models are highly interactive, with small events causing state changes. Thus they claim that management should be "event-driven". Their model addresses the impact of fire and rainfall and emphasises the competition between shrub and grass. The aim of their modelling was to find optimal patterns of stocking and burning through solving a discrete optimisation problem using the model.

Another approach is to consider the grassland, the pastoralists and the policy-makers as a complex adaptive system (Janssen et al. 2000). One means of studying complex adaptive systems is adaptive agent models, which simulate a population of diverse and interacting agents. In the model the behaviour of individual agents lead to emergent properties at higher levels. In Janssen et al. (2000)'s modelled rangeland system, ecological and socio-economic sub-systems are identified. The ecological model is borrowed from previous comprehensive models, while the socio-economic model describes the policy and institution environment and the behaviour of pastoralists. Although significantly simplified, such models can illustrate how the management policy influences the system's state and agent's behaviour. Compared to traditional ecological models and optimal control models, the adaptive agent models allow more profound examination into the different results of policies and how policies evolve, by incorporating agents and their behaviours into the model.

The state-transition models, along with more traditional succession models, arguably lack some spatial and temporal context. Some researchers argue that given a larger spatial scale of disturbance, the system will appear as a non-equilibrium one, while in extended time frame, event-driven changes become continuous (e.g. Friedel et al. 2001). To address the non-equilibrium dynamics, equilibrium-based succession models are not sufficient. Novel vegetation dynamic models nowadays usually support simulation of non-equilibrium processes. These models achieve this by including vegetation physiology and biophysics, vegetation phenology and nutrient cycling (Cramer et al. 2001), many of which can be incorporated into atmosphere-biosphere models, or use their outputs. The main problem with these models is that their complexity has a negative effect on computation efficiency, and demands substantial data from multiple sources. Most of these models are applicable to many vegetation function groups. Those emphasising grassland simulation usually also incorporate grazing and other anthropogenic interactions.

In order to solve the problem brought by dynamic model's substantial demand on data in the parameterisation process as well as repeated parameterisation caused by heterogeneity of study locations, stochastic models, which use statistical means to describe data, are proposed and examined in various settings to provide a simplified yet credible means to simulate vegetation status. An example of such model is the herbage production model developed by Trnka et al. (2006). The model utilises water availability and solar radiation data from observations and describe them with statistical terms. The interactions between weather, water availability and management regimes are simulated in the reliable grassland statistical model (GRAM), and run with both a polynomial regression and neural networks approach. Furthermore, the GRAM model was coupled with a statistical meteorology model to simulate how weather conditions and disturbance affect grass production. Statistical models are by design consistent with resilience assessment, as they simulate changes and transient conditions and yield results on how the system components respond. However, for models like GRAM, despite the fact that detailed parameterisation is no longer needed, the problem is that its calibration and verification can only be done with experimental data, and the experimental process has to be carried out every time the study location is changed (Trnka et al. 2006), causing other data requirements. Besides, the representativeness of these experimental data cannot be guaranteed in small scale experiments, thus leading to the question of the model's accuracy. Given these difficulties, GRAM performed reasonably well in European settings and was tested under various grassland conditions. Similar statistical models may also be used in semi-arid grassland environments.

Another direction of modellers' efforts is in models that use remotely sensed data. The ability of remote sensing means to collect surface data from a vast area partly meets the requirement of some dynamic or stochastic models to obtain large amounts of data in parameterisation and calibration. However, it should be noted that remotely-sensed data need calibration and validation themselves. And it is still difficult to obtain both vegetation and soil data in exactly the same conditions due to the fact that sensors for these data are usually on different platforms, each with their own orbit, passing time and observation angles. Thus these models often focus on vegetation's above ground biomass and cover with less attention on soil conditions. Usually these models are more used in land cover analysis and change detection of vegetation's above ground cover. For example, the Sahelian Transpiration Evaporation and Production (STEP) model is coupled with a radiative transfer model, which utilises radar-based remotely sensed data to provide information on herbaceous biomass and water availability in vegetation and soil (Jarlan et al. 2005, Mangiarotti et al. 2008). In areas with relatively little change in soil conditions, it is useful to utilise these remote sensing-based models to achieve fast model development.

3.2 Remote sensing as a means of collecting resilience data

Remote sensing has been defined as "the practice of deriving information about the earth's land and water surfaces using images acquired from an overhead perspective, using electromagnetic radiation [...] reflected or emitted from the earth" (Campbell 2002, p.6). In practice, the concept of remote sensing covers observation from various platforms, although satellite remote sensing is still one of the dominant and fast-developing branches. In ecological and environmental studies, it is often desirable to obtain data from a large area, or data within a spatial context. Due to the advantage of the remote sensing approach, these studies often directly or indirectly utilise remotely sensed data. Driven by study needs, the science and technology behind remote sensing has progressed in recent decades, allowing more sophisticated and creative applications.

The study of social-ecosystem resilience requires a means of holistic assessment and the ability of observing fast changing phenomena. With a carefully designed methodology, remote sensing can help meet these requirements and can become an important assessment and monitoring tool. Although it is not practical to directly observe resilience with remote sensing, it is possible to observe landscape patterns, changes and restoration of surrogates, and vulnerability through remote sensing. Some of the techniques and examples of applications are reviewed below.

3.2.1 AVHRR sensors and platforms

The assessment of resilience can take place at various scales. Accordingly, a range of platforms and sensors with varying spatial, spectral and temporal resolutions can be used. In this section one of the most common general sensors, namely Advanced Very High Resolution Radiometer (AVHRR) series are discussed.

One of the most commonly employed general-purpose remote sensing platforms is the National Oceanic and Atmospheric Administration (NOAA) series of satellites, with the AVHRR sensors onboard. The AVHRR was designed to observe cloud cover and surface temperature at first. However it was not long before the data are used for vegetation remote sensing. The first AVHRR was a 4-channel radiometer, carried on the TIROS-N satellite and was launched in October 1978. Later in June 1981 AVHRR/2 with 5 channels was carried on the NOAA-7 satellite. The last instrument is AVHRR/3, with 6 channels and was carried on the NOAA-15 launched in May 1998 (National Satellite Services Division 2007). The AVHRR provides complete coverage from pole to pole (Campbell 2002). The typical spatial resolution at nadir is 1.09 km. The bands used by the three AVHRR

Table 3.1: AVHRR Channel Characteristics (Cracknell 1997, National Satellite Services Division 2007), numbers are wavelengths in micrometre (μm).

Channel	NOAA-6 -9 -12	NOAA-7 -8 -10 -11 -13 -14	NOAA-15 -16 -17	Typical Use
1	0.58 – 0.68	0.58 – 0.68	0.58 – 0.68	Daytime cloud and surface mapping
2	0.725 – 1.10	0.725 – 1.10	0.725 – 1.10	Land-water boundaries
3A	N/A	N/A	1.58 – 1.64	Snow and ice detection
3B	3.55 – 3.93	3.55 – 3.93	3.55 – 3.93	Night cloud mapping, sea surface temperature
4	10.50 – 11.50	10.30 – 11.30	10.30 – 11.30	Night cloud mapping, sea surface temperature
5	Channel 4 repeated	11.50 – 12.50	11.50 – 12.50	Sea surface temperature

sensors and their vehicles are listed in Table 3.1.

AVHRR data are among the most extensive and consistent data series remote sensing can provide. However, raw data and low-level data generally need processing against the effects of atmosphere and solar radiation conditions. The production of more thoroughly processed data requires a large amount of supplementary data and intensive computation and can take months. The levels of AVHRR data include Automatic Picture Transmission (APT) read directly by ground stations, Global Area Coverage (GAC), High Resolution Picture Transmission (HRPT) and Local Area Coverage (LAC), with GAC and LAC derived from APT and HRPT, respectively. Aside from these, there are also third-party derived data sets, such as Pathfinder, Global Inventory Modeling and Mapping Studies (GIMMS) data set and the Fourier-Adjusted, Sensor and Solar zenith angle corrected, interpolated, Reconstructed (FASIR) data set.

The AVHRR vehicles orbit round the earth about 14 times per day, with a swath of about 2,399 km wide. The advantages of AVHRR data and its derivative products thus include high temporal resolution, high consistency of images, well-developed correction procedures, and pole-to-pole global coverage. The spatial resolution is suitable for its original purpose of observing large weather systems as well as for ecosystem monitoring, although interactions taking place in a smaller space would need finer resolution.

3.2.2 Deriving NDVI and meteorological data from AVHRR imagery

In order to quantitatively study vegetation cover from remote sensing imagery, a measurement of vegetation cover and state is needed. The vegetation index is an answer to this need. The assumption on which vegetation indices are based is that different surfaces, and vegetation in different states, have varying responses in multispectral remote sense imagery. Therefore, some arithmetical combination of spectral bands should be able to reveal information about vegetation structure and the state of vegetation. It has been noted that vegetation generally has high reflectance in near-infrared wavelength and low reflectance in red wavelength (Figure 3.1), thus the difference between infrared and red reflectance can be considered to be a "signature" of vegetation cover. Moreover, the extent of the difference can serve as indicators of the density of the cover and health of vegetation (Liang 2004). As a result, a series of vegetation indices utilise infrared and red reflectance.

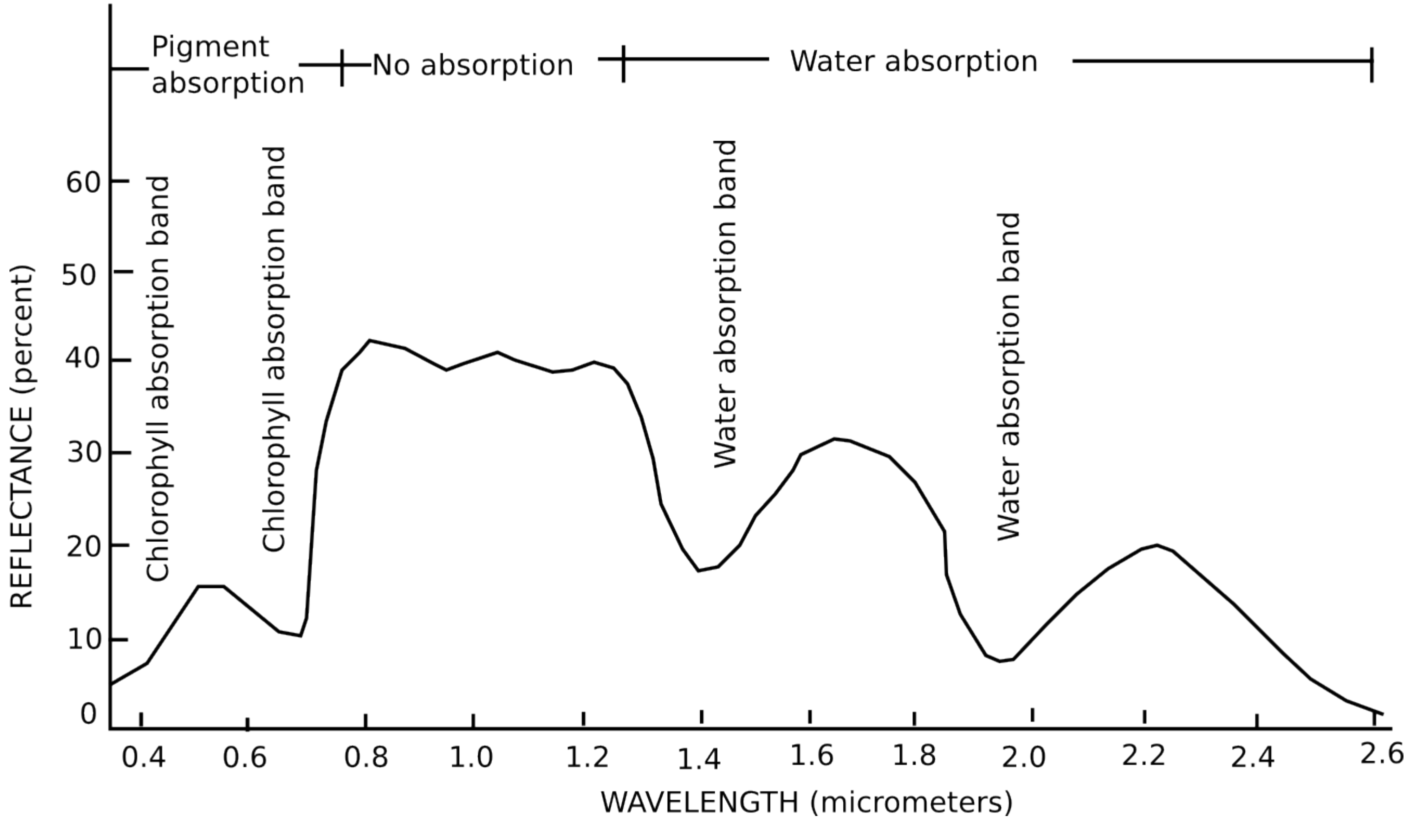


Figure 3.1: A typical response curve of vegetation. Note low reflectance near 0.65 µm (red) and high reflectance at 0.8 – 1.2 µm (near infrared) wavelengths. Adapted from McCoy (2004).

Among these indices, the Normalized Difference Vegetation Index (NDVI) is one of the earliest and very widely used in various applications. It has been considered as a good indicator of various vegetation parameters, including green leaf area index (LAI), biomass, percent green cover, and green biomass production (Anyamba and Tucker 2005). For grasslands, the development of canopy and photosynthetic activities are generally in synchrony, and NDVI provides close estimates of aboveground net primary productivity (ANPP) (Paruelo et al. 1997). Therefore NDVI is a suitable indicator of ground vegetation growth on grasslands, although the impact of soil may be larger in some areas. It is easy to implement and calculate, and can be effective in situations in which the canopies are neither too sparse nor too dense. NDVI is defined as

$$\frac{\text{infrared reflectance} - \text{red reflectance}}{\text{infrared reflectance} + \text{red reflectance}} \tag{3.3}$$

and in theory has a range of -1 to 1 (Liang 2004). Channel 1 and 2 of AVHRR sensor are in the visible and near-infrared ranges of spectrum without overlapping (Tucker et al. 2005), which implies that AVHRR imagery can be used to derive NDVI calculations.

AVHRR-derived global land surface NDVI datasets include the NOAA Global Vegetation Index (GVI) (Kidwell 1997), the NASA AVHRR Land Pathfinder (ALP) 8-km resolution dataset I and II (McManus et al. 2001, Ouaidrari et al. 2003), the Global Inventory Monitoring and Modeling System (GIMMS) dataset (Tucker et al. 2005) and Fourier-Adjusted, Sensor and Solar zenith angle corrected, Interpolated, Reconstructed (FASIR) NDVI dataset (Los et al. 2000). These datasets' attributes are summarised in Table 3.2.

Table 3.2: Comparison of some AVHRR NDVI datasets

Name	Spatial resolution	Temporal resolution	Temporal coverage	Notes
First Generation GVI	4 km	Daily/ Weekly	May 1982 – April 1985	
Second Generation GVI	13 – 19.5 km	Weekly	April 1985 – Present	Scan angle correction and look-up table correction
Third Generation GVI	0.15 °	Weekly	April 1985 – Present	With quality/-cloud data for each cell
ALP I & II	8 km	Daily/10-day composite	July 1981 – Present	ALP II has water vapor correction
GIMMS	8 km	15-day (bimonthly) composite	July 1981 – Present	10-day composite for Africa are available
FASIR	0.25 °	10-day composite	January 1982 – December 2006	Corrected for solar zenith angle, outlier values and land cover classification

GIMMS and FASIR datasets have undergone various calibration and correction process and address most of the issues in AVHRR data, therefore the processing of the two datasets is briefly reviewed. GIMMS was produced by ingesting AVHRR level-1b data, which contain geophysical calibration for infrared and near-infrared channels and geolocation information (Goodrum et al. 2000). Although AVHRR covers a wide swath of land in one pass, only data with scan angles $< \pm 40^\circ$ were used to reduce distortion in the geometry of the images. The pixel values were forward mapped to the output bin, meaning the location of measurements was determined by the location of output bins (Liang 2004) of equal area grid cells.

The data then underwent a series of calibration and correction processes. Using the orbital model of AVHRR carriers, with the satellite onboard clock and orbital elements as input, the position of the satellite and the sun-target-sensor geometry can be calculated for geometric correction (Tucker et al. 2005). The effect of orbital drift of some NOAA satellites was also addressed. The highest NDVI value calculated for each pixel using data collected in half a month was used as the representative value in the bimonthly composite images. By doing so some influence of cloud and aerosol on NDVI values may be removed. But the constant impact of sensors and aerosol cannot be removed by such means (Tucker et al. 2005).

The composite images were then manually checked for its geometric accuracy by comparison with coastline reference for every continent (Tucker et al. 2005). If any inconsistency larger than 1 pixel was identified, the daily images involved in making the composite were investigated and the ones with such error identified. If the error cannot be adjusted, the image from that day had to be discarded. The empty values, bad scan lines and strange values were mostly corrected.

The radiometric calibration was done in different ways for old and newer NOAA satellites. For NOAA-7 through NOAA-14, AVHRR channel 1 and 2 data were firstly intercalibrated using high altitude (> 12 km) bright clouds as "white" targets, and calibrated using off-nadir (40 ° – 70 °) deep ocean radiance to remove aerosol effects. The net signal in channel 1 was then used to remove Raleigh scattering in channel 2. The effect of these steps was an absolute calibration for both channels (Vermote and Kaufman 1995). For NOAA-16 and -17, the pre-flight calibration parameters for channel 1 and 2 were used. The NDVI data derived was then intercalibrated with NDVI time series derived from images taken by French Le Système pour l'Observation de la Terre (SPOT, meaning Earth Observation System), which had been adjusted to match NOAA-14 NDVI results. By doing so the NOAA-16 and -17 results were linked with NOAA-14 results. This was necessary due to the fact that NOAA-16 and -17's instruments were not linearly adjusted to match previous instruments (Tucker et al. 2005).

The atmospheric correction mainly consisted of correction for El Chichon and Mt Pinatubo volcanic aerosol effects. The correction was done for images taken in the periods from April 1982 through December 1984 and from June 1991 through December 1993. Cloud screening was done using AVHRR channel 5 (thermal) data. Maximum value compositing was considered to be able to minimise atmospheric and directional reflectance effects. Due to lack of data, explicit correction for these effects could not be done, but the data producer suggested doing so in the future (Tucker et al. 2005).

In summary, GIMMS datasets have undergone both relative and absolute calibration, accurately registered to geographic locations, and corrected for the change of orbit and major atmospheric effects. FASIR datasets used GIMMS data as their primary data source, but incorporated land cover classification information to address biome dependencies and parameters in the NDVI corrections (Los et al. 2000). FASIR datasets also used Fourier adjustment to identify and correct outlier values and short-term atmospheric aerosols. The GIMMS and FASIR datasets include corrections for solar zenith angle and viewing angle. Both GIMMS and FASIR datasets are considered suitable for environmental change studies (e.g. Angert et al. 2005, Bondeau et al. 1999) as they provide relatively long records of NDVI changes with considerable consistency. The other datasets such as GVI and ALP are also widely used, but when studying long-term changes, more work needs to be done to ensure their consistency and stability (e.g. Di and Hastings 1995, Prince and Goward 1996).

3.2.3 Evaluating grassland vegetation state from NDVI imagery

The changes in vegetation growth and canopy structure are often reflected in the changes of NDVI values, because the water or chlorophyll content in the plant is changed. Therefore NDVI images can be used to assess the condition of vegetation if a relation between an indicator of vegetation phenology and NDVI values can be established (Campbell 2002, p.470).

NDVI has been commonly used to estimate vegetation biomass and natural primary productivity. Studies have identified a positive relationship between NDVI derived from AVHRR images and either biomass or above-ground net primary productivity (ANPP). In a study by Paruelo et al. (1997), the annually integrated NDVI and ANPP were found to have a significant and positive relationship in grassland areas with a mean annual precipitation between 280 and 1150 mm, and mean annual temperature between 4 °C and 20 °C. It must be pointed out that the relationship between NDVI and ANPP is not linear over the range of ANPP. NDVI can be influenced by reflectance from the soil in biomes with low ANPP.

The signal from vegetation may be indistinguishable from those from the background. If ANPP is high the NDVI response may be saturated, with little NDVI gain if ANPP increases. Grassland has ANPP values between these extremes, and may be the most suitable biomes to derive estimations of ANPP from NDVI data (Paruelo et al. 1997).

Aside from direct estimation of ANPP based on NDVI values and ground measurement, NDVI data can also be used to estimate absorbed photosynthetic active radiation (APAR), which is a useful component in models that calculate ANPP. Gamon et al. (1995) found that both NDVI and Simple Ratio of near infrared reflectance to red reflectance are near linearly correlated with APAR over a wide range of canopy densities. Maximum daily photosynthesis rate is positively correlated with NDVI in most grassland and semideciduous shrubs, because their canopy development and photosynthesis are in synchrony (Gamon et al. 1995).

NDVI imagery is often used to study the phenology of deciduous and grassland vegetation. These vegetation types have a "green-up" process at the beginning of their growing season, and turn yellow at the end of the growing season. By looking at the curve of their NDVI fluctuation, annual trends of sudden increase and decrease of NDVI values can be identified. These trends are considered to be the indicator of the plant's phenology patterns. Remote sensing also enables the researchers to study the spatial patterns of phenology variations, and link them with other spatial parameters such as topography and precipitation (Lee et al. 2002).

The influence of El Niño/La Niña phenomena is often pronounced in the form of change of precipitation. Such changes, if they coincide with vegetation's growing period, can have significant effects on observed NDVI values. In different areas El Niño/La Niña have varying effects on precipitation. Thus they also cause increase or decrease in NDVI differently. The effect of El Niño/La Niña may also be combined with that of monsoons (Weiss et al. 2004).

3.2.4 Remote sensing of spatial patterns and changes

The occurrence and distribution of disturbances are often regarded as indicators of a system's state and resilience. Therefore, in resilience studies it is common to examine spatial patterns of disturbance and derive measurements of resilience based on its definition. Because digital remotely-sensed imagery can be directly expressed as a grid of values, and can be transformed into meaningful indicators such as NDVI, remote sensing has made such pattern studies more efficient. The description of pattern characteristics is also facilitated by combining remote sensing imagery with statistics software packages.

One approach to studying patterns and changes is based on the idea of landscape states and thresholds beyond which a state transition will take place. This involves first establishing criteria of states and vulnerability. The process taking place in the landscape is understood through finer-scale observations, with the issue of heterogeneity addressed by constructing a hierarchical, multivariate structure of regions. An adequate ecosystem model that can describe the mechanisms should be matched to the system. Based on the ecosystem model and a state-transition description of the system, various states and their correspondent measurements may be identified according to the criteria and thresholds. Finding the indicator is seldom straightforward, but it is argued that given the management goal and the right ecosystem model, the indicators derived can describe differences in the likelihood of ecosystem responses (Bestelmeyer et al. 2008). The collection of indicator values can be done through remote sensing for the area. The hierarchical landscape regions can then be recognised as a hierarchical mosaic of states. The "state map" then provides an explicit illustration of risks of deterioration and restoration constraints. The scale of state mosaics also gives a hint on the scale of processes. To fully understand the form of state mosaics, a social-ecological model should be combined to the state-transition model and the motives of individual land users should be understood (Bestelmeyer et al. 2008). After these steps, the social and ecological threshold for each state mosaic may be identified and the region's resilience assessed.

To successfully apply this approach the researcher needs to obtain various landscape data such as land use/cover types, energy and water distribution as well as vegetation state and other gradients. It is not possible to adopt a regional view of the system and avoid a point-based view if remote sensing is not employed in data collection. And a regional perspective is a prerequisite to establish a meaningful mosaic of states.

Another approach is inspired by the idea that human actions and disturbances determine the constraints imposed on smaller socio-ecological systems by larger ones (Zurlini et al. 2006). It is believed that changes in human actions and disturbances can lead to the change in the structure and dynamics of the entire socio-ecological system, thus it is desirable to measure and monitor the disturbances if the researcher wants to assess the system's resilience. What constitutes disturbance is again dependent on the management goal. In some circumstances, the disturbance can be measured by remote sensing. In order to address cross-scale effects of disturbance, a scalable moving-window method is often implemented. In a study of a southern Italian crop-woodland socio-ecological system, NDVI values were used as an indicator of disturbance and the moving-window method was employed (Zurlini et al. 2006). The researchers defined disturbance as a standardised difference in NDVI values beyond a given percentage between two different times at the same location, as the difference was considered to reflect detectable changes in land use or land cover. Around each pixel in the remotely sensed NDVI image a set of 10 windows with different sizes from 3×3 to 225×225 pixels was established. Within each window the proportion of disturbed pixel (Pd) and adjacency of disturbance (Pdd) were calculated. These two measurements of 10 window sizes comprised the disturbance profile for a location. Using cluster analysis, locations with similar profile could be identified, while the clustered map could be compared with known spatial patterns to identify possible links between spatial distribution and resilience. If all combinations of Pd and Pdd were drawn on a scatter plot, the researchers found that they tend to appear in an ellipse with the line Pd = Pdd as its main axis (Zurlini et al. 2006). Thus the researchers argue that areas with high Pd and Pdd are less resilient and resilience can be attributed to different types of disturbance profiles. Examining the geographic correlation of disturbance profiles thus helps them understand how land use types and management practices affect resilience in the area. The change of Pd and Pdd with window size illustrates multi-scale patterns of disturbance and can give hints about the underlying driver of disturbance. This approach provides a tangible measurement of fragility, which reflects some intrinsic factors of resilience. It also illustrates how resilience can change spatially with pressures and resistances.

More commonly, in many studies, resilience indicators are considered equivalent to an indicator that can be directly derived from the remotely sensed image, such as vegetation indices. For example, Baum and Germino (2005) observed modified soil-adjusted vegetation index ($MSAVI_2$) change from Landsat imagery and found that recurring disturbance increases the sensitivity of steppe to changes in precipitation, which in essence is equal to reducing the size of domain of attraction, therefore reducing resilience. A similar methodology is used by other researchers. Despite its intuitiveness, this methodology does not consider the social factor which is an inseparable part of the system, nor does it address the spatial presentation of human influence such as land use types. As a result it brings certain biases into the analysis unless the system in question is totally “undisturbed”, which is a rare and questionable phenomenon. Besides, this approach also leads to the possibility that the researcher and the manager may be actually looking at engineering resilience rather than ecological resilience. The patterns and changes observed by remote sensing in resilience studies should not only be biophysical, but also socio-ecological.

Chapter 4

Methodology

In order to assess the resilience of the area in question, the annual pattern of vegetation index and net primary productivity were identified from remotely sensed imagery. Then the patterns of disturbance were identified and analysed. A conceptual model provided information on the components and interactions of the system and how they are influenced by the disturbances. The knowledge was used in the design and parameterisation of a dynamic model, which simulated grassland productivity's change, with consideration of impacts of policy changes on resilience.

4.1 Data sources

4.1.1 Remotely sensed data

The remote sensing data used in the study is mainly NDVI data derived from AVHRR satellite images. AVHRR data is available in various formats with different degrees of processing and spatial/temporal resolution. However, the data directly obtainable from NOAA, United States, do not address various atmospheric effects, nor do they address the inconsistencies due to instrument's degradation and change throughout the time series, rendering comparison and further analysis difficult. To correct these inconsistency involves using complicated models, and is not included in the scope of the study. Thus datasets derived from AVHRR LAC data were used.

The datasets considered in the study included the Fourier-Adjusted, Sensor and Solar zenith angle corrected, Interpolated, Reconstructed (FASIR) adjusted NDVI dataset provided by the International Satellite Land-Surface Climatology Project, Initiative II Data Archive (ISLSCP II), which covers data collected from 1982 to 1998 (Los et al. 2000), and the Global Inventory Modeling and Mapping System (GIMMS) half-monthly composite NDVI data (Tucker et al. 2005), which was obtained from the Global Land Cover Facility (GLCF, `http://www.landcover.org`), University of Maryland, covering data collected from 1981 to 2003. The FASIR dataset can be considered as derived from GIMMS dataset and incorporating Fourier adjustment to address the occurrence of NDVI outliers with extremely high values. The process to derive the FASIR data set involves resampling the data from 8-km resolution to 0.25° or 1°. As a result the spatial resolution of FASIR is lower than that of GIMMS (8-km). However, a comparison showed that in this area the FASIR dataset does not have an advantage over GIMMS or other datasets in terms of removing extreme values. GIMMS, on the other hand, provides better temporal coverage than the FASIR dataset and better spatial resolution, which are favourable in time series analysis. Therefore the study chose the GIMMS dataset.

4.1.2 Qualitative descriptions, statistics and primary knowledge from fieldwork

The description of Tibetan nomadic pastoralism mainly came from accounts of geographers and anthropologists such as Goldstein and Beall (1991) and Miller (1999*b*), who have lived with Tibetan pastoralists during their study. Their description of the pastoralists' life conform to the researcher's experience. The historical account of the area was mainly composed from various sources such as Stein (1972) and Grunfeld (1996), who mainly studied the area using archives and literature. The researcher also accumulated some observational data and anecdotes from his experience travelling in Tibet and living with Tibetan pastoralists. Such information was critical in the making of conceptual models.

The researcher travelled in the TAR in 2003 and 2005, and in Qinghai Province on the northern Tibetan Plateau in 2004. While the trip in 2003 was for mountaineering exclusively, the 2004 and 2005 trips focused on investigating pastoralism impacts on the environment and the reform of pastoralism on the plateau. The 2004 trip was made due to concern for the said grassland degradation due to overgrazing in the source area of China's major rivers. The 2005 trip was in the interest to observe the changes caused by the construction of the Qinghai-Tibet Railway and its potential in altering the outlook of the social-economic conditions of the area. In both trips the researcher and his teammates conducted interviews using designed questionaires with various stakeholders including pastoralists, merchants, miners and government officials. In the 2005 trip the researcher also had the opportunity to live with a relatively well-to-do pastoral family, conduct unstructured interviews and experience the pastoralists' life. All interviews were conducted in an overt manner, sometimes in the company of an government official as the interpreter. In the observation of the local environment the researcher also identified the qualitative effect of precipitation, the recovery of grassland after drought, and the impact of the population fluctuation of plateau pika (*Ochotona curzoniae*). The ways in which local people and government manage pasture resources were also observed and recorded. The understanding gained in the two trips was the foundation of the conceptual model discussed in Section 4.5.

Some general statistics of the TAR was obtained from newspapers, magazines and websites, as well as compilations such as *Tibetan Sourcebook* (Nai-Ming 1964). These statistics provide information on the trends of local productivity and economy.

4.2 Exploratory processing of remote sensing data

4.2.1 Basic statistics

Descriptive statistics were conducted on remotely sensed data, with a focus on El Niño phenomenon and its impact. A comparison of GIMMS and FASIR data was first conducted to evaluate their properties and determine which is more suitable for the study. Using data from the same period of time (July 1998), the maximum values and distributions of the two datasets were compared. The discrepancies between the two datasets and their distribution were also examined.

In terms of the El Niño phenomenon, both datasets were compared on their signal response to El Niño maxima. The average values of different regions in El Niño and non-El Niño years were investigated to see which data set captures the change brought by El Niño better. The correlation between remote sensing datasets and temperature/precipitation data was also compared in an attempt to see if any dataset has a better correlation with the meteorology data.

In order to avoid the over-generalisation of climate characteristics in different regions in Tibet, the images covering the whole Tibetan Plateau were split into 4 subareas, covering Eastern, Western, Northern and Southern Tibetan Plateau. The dimensions and location of each image patch are summarised in Table 4.1. The same descriptive statistics used on the

Table 4.1: Boundaries of subarea patches

Subarea	North	South	East	West	No. of pixels
Eastern TP	40 °N	27 °N	104 °E	95 °E	22196
Western TP	40 °N	32 °N	86 °E	71 °E	22660
Northern TP	40 °N	32 °N	95 °E	85 °E	13640
Southern TP	32 °N	27 °N	95 °E	71 °E	22770

whole area's images were also used on subarea ones.

4.2.2 NDVI anomaly

Both GIMMS and FASIR datasets were used to calculate NDVI anomalies, which is defined as

$$NDVI_\sigma = (\frac{NDVI_\alpha}{NDVI_\mu} - 1) \times 100 \qquad (4.1)$$

where $NDVI_\sigma$ are the growing season anomalies, $NDVI_\alpha$ are individual seasonal means and $NDVI_\mu$ is the long-term growing season NDVI mean calculated using growing season data between 1981 and 2003 from the whole available dataset. NDVI image data for the growing season (June to September) were selected to calculate $NDVI_\alpha$ and $NDVI_\mu$. $NDVI_\sigma$ was calculated using equation (4.1) for every valid pixel in each frame. This approach therefore provided a visual presentation of NDVI changes in each year. The effects of El Niño and the geographic location of impacts could be identified from the map generated from $NDVI_\sigma$ data. The anomaly of NPP could be calculated in a similar manner.

4.3 Derivation of net primary productivity data from NDVI

The Carnegie-Ames-Stanford Approach (CASA) provides a means to estimate net primary productivity (NPP) from NDVI data, temperature and moisture measures. It puts emphasises more on climate and resources aspect, and less on biome type (Field et al. 1995), thus it is probably more suitable for the research area, which has relatively uniform biome types and is mainly limited by resource and energy availability. The CASA model can be expressed by the following equation:

$$NPP(x,t) = APAR(x,t) \cdot \epsilon(x,t) \tag{4.2}$$

where (x,t) denotes a location (x) at time (t); $APAR$ is the amount of photosynthetically active radiation (PAR) absorbed by green vegetation; ϵ is the efficiency by which the radiation is converted to plant biomass (Field et al. 1995). The equation can also be written as

$$NPP = S(x,t) \cdot FPAR(x,t) \cdot \epsilon^* \cdot T_1(x,t) \cdot T_2(x,t) \cdot W(x,t) \tag{4.3}$$

where $S(x,t)$ is PAR surface irradiance, calculated as half the total solar surface irradiance; $FPAR(x,t)$ is a linear function of the simple ratio vegetation index (SR); ϵ^* is the globally defined maximum light use efficiency; $W(x,t)$ is the water scalar, and is calculated using estimated evapotranspiration (EET) and potential evapotranspiration (PET) in this equation:

$$W(x,t) = 0.5 + EET(x,t)/PET(x,t) \tag{4.4}$$

where PET is the function of temperature and latitude, while EET is related to both precipitation and evaporation from the soil. T_1 and T_2 are only related to the mean temperature (°C) during the month of maximum NDVI, and are calculated as:

$$T_1(x) = 0.8 + 0.02 \times T_{opt}(x) - 0.0005 \times [T_{opt}(x)]^2 \tag{4.5}$$

$$T_2(x,t) = C \cdot 1/\{1 + exp[0.2 \cdot (T_{opt}(x) - 10 - T(x,t)]\} \\ \cdot 1/\{1 + exp[0.3 \cdot (-T_{opt}(x) - 10 + T(x,t)]\} \quad (4.6)$$

where $T_{opt}(x)$ is the optimum temperature at location x, here estimated using highest temperature in the whole time series.

However, the implementation of the CASA model was hindered by the lack of availability of detailed meteorological data of Tibet to users outside China. Therefore some approximation and estimation were employed. The FPAR could be coarsely fitted from SR values, assuming a linear relationship, or from scaled NDVI data, considering the influence of atmosphere irradiance (Olofsson and Eklundh 2007). The NDVI values representing maximum and minimum FPAR were identified by finding percentiles of NDVI for each land cover type. The percentile was determined by the vegetation morphologies of concern. Assuming the vegetation has similar NDVI response to seasonality, the maximum and minimum NDVI values defined by the percentiles should have similar fluctuations as seasons shift. The upper percentile was set to 100%, as the maximum NDVI does not exceed 0.8 in FASIR data set and is considered as generated by vegetation. The lower percentile was determined through a series of experiments. For each land cover type, its FPAR was calculated as:

$$f_a(i,j,k) = 0.95 \frac{NDVI(i,j) - NDVI_{lp,k}}{NDVI_{100,k} - NDVI_{lp,k}} \quad (4.7)$$

where $f_a(i,j,k)$ and $NDVI(i,j)$ are the FPAR and NDVI for land cover type j in the ith frame in the time series, $NDVI_{lp,k}$ is the NDVI value at the lower percentile at pixel k, $NDVI_{100,k}$ that at the maximum at pixel k, 0.95 is the empirical value of FPAR assuming maximum possible utilisation of solar active radiation by the vegetation.

The land cover information was obtained as a processed AVHRR land cover map from Global Land Cover Facility, University of Maryland (Hansen et al. 2000). This map was chosen because there are few land cover maps covering the study area with adequate resolution that are available to the researcher and can be easily digitized. The land cover information in the map is generally consistent with maps produced in China (*China Atlas* 1979). The map shows that the study area has 8 major land cover types, namely woodland, wooded grassland, closed shrubland, open shrubland, grassland, cropland, bare ground and urban (Figure 4.1). Based on the classification, the GIMMS images were stratified into 8 portions, with NDVI percentiles calculated for each. The FPAR was then calculated using Equation 4.7 for each land cover type. The results were then combined into one image.

To obtain $S(x,t)$ in equation (4.3) the total solar irradiance (TSI) data were needed. A composite database provided at National Geophysical Data Center (NGDC) of China was used. The data set was prepared by Fröhlich and Lean (1998), and used data from Physikalisch-Meteorologisches Observatorium Davos/World Radiation Center (PMOD/WRC) in Davos, Switzerland, as well as data from the VIRGO Experiment on the ESA/-NASA cooperative Mission SoHO. The data entries were on a daily basis and were aggregated for every 15-day period in order to be consistent with NDVI data. In this data set TSI values after 1st October 2003 were not available, which were estimated by comparing TSIs in earlier months in 2003 with those in the corresponding months in other years to obtain an averaged coefficient, and multiplying the other years TSIs after 1st of October by the coefficient.

To calculate scalar W and T, various data were needed, including estimated evapotranspiration (EET), potential evapotranspiration (PET), and temperature data. The PET data was obtained from the United Nations Environment Programme's GRID Archive (Ahn and Tateishi 1994,

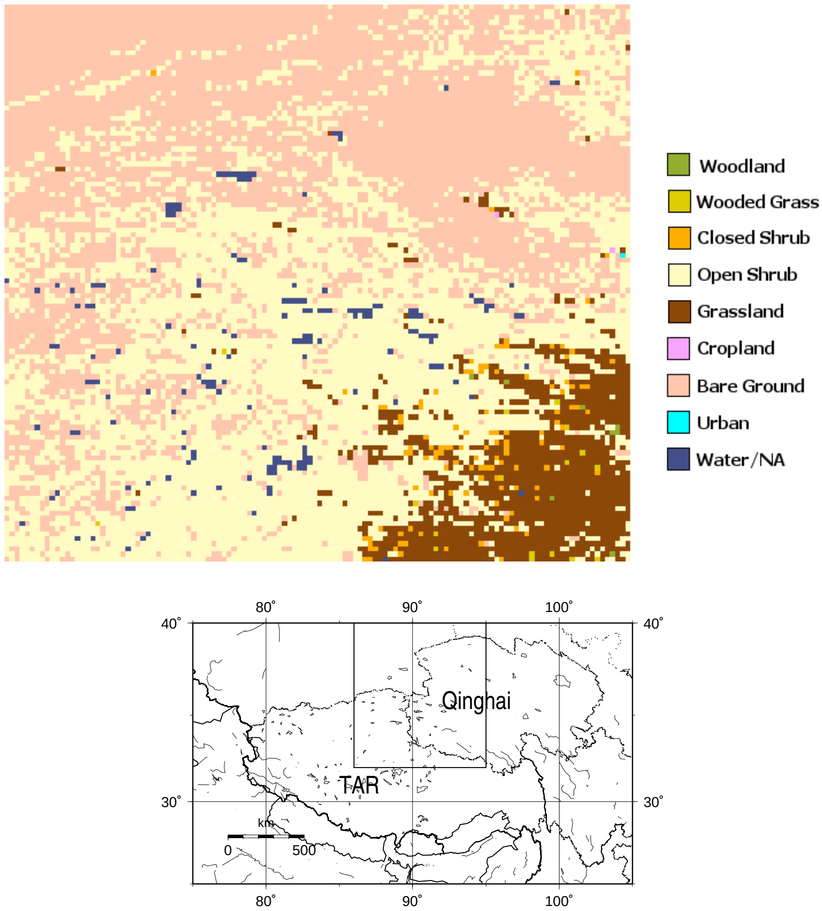


Figure 4.1: The land cover map of Northern Tibetan Plateau, drawn using data from Hansen et al. (2000). The extent of the image is indicated by the box in the small map. The location map used here and other figures was drawn with GMT (Wessel and Smith 1991, Wessel 2007) using the GSHHS shoreline data (Wessel and Smith 1996).

United Nations Environment Programme Global Resource Information Database 2004); the estimated evapotranspiration values were extracted from GLDAS data sets, a part of the mission of NASA's Earth Science Division, archived and distributed by the Goddard Earth Sciences (GES) Data and Information Services Center(DISC). Some unavailable entries in the data set were estimated by averaging corresponding data from the next and previous years' data. The calculation was conducted using equation 4.4, 4.5 and 4.6 in a GIS software environment. It was then possible to calculate NPP using FPAR, TSI and these scalars. The anomaly of NPP was calculated in a way similar to that of calculating the NDVI anomaly.

4.4 Spatial analysis

In order to study the resilience of the current natural and social system, and the possible consequence of institutional and natural changes, it is necessary to first identify the pattern of disturbances. By having knowledge of the probability and intensity of disturbance, and the system's vulnerability to disturbance, the factors contributing to gain and loss of resilience can be inferred. Two techniques were used on the NDVI and NPP imagery to identify characteristics of disturbance on the plateau. Detrended Fluctuation Analysis (DFA) is based on the power-law relationship of probability and intensity of many natural disturbances, and can reveal information on the probability of large disturbances in the future, given disturbances that already have taken place. Trend analysis is a simple measurement of consecutive increasing or decreasing trend in a given time period. The two analyses characterised disturbance in terms of probability and intensity. When combined with spatial information, they may also provide information on spatial patterns of disturbances.

4.4.1 Detrended Fluctuation Analysis

DFA was first derived by Peng et al. (1994) in the study of DNA nucleotides' organisation and "patchiness". The method allows researchers to identify long-range power-law correlations in time series from those which have no correlations but white-noise. Because many phenomena in the nature can be described as $1/f^{\alpha}$ noise, DFA can potentially be used to find the relationships between fluctuations and time scale in these phenomena. The method was later adopted by Telesca et al. (2006) in the study of forest ecosystem's long-term trend in the face of perturbations expressed in the form of NDVI data.

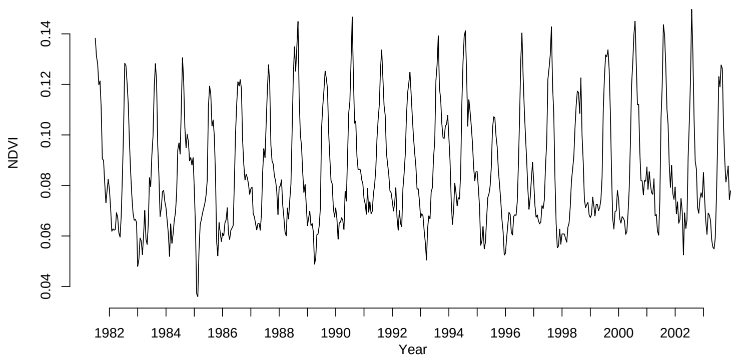
DFA was conducted using monthly averaged data over the area. The mean NPP value of each month was calculated first. Because of seasonality, NPP data has natural fluctuation trends, which must be eliminated by subtracting from each month's data the average of the month's values over all the years concerned (Figure 4.2). The fluctuation of monthly time series from the mean values was at first integrated (Peng et al. 1995):

$$y(k) = \sum_{i=1}^{k} [x(i) - x_{ave}] \tag{4.8}$$

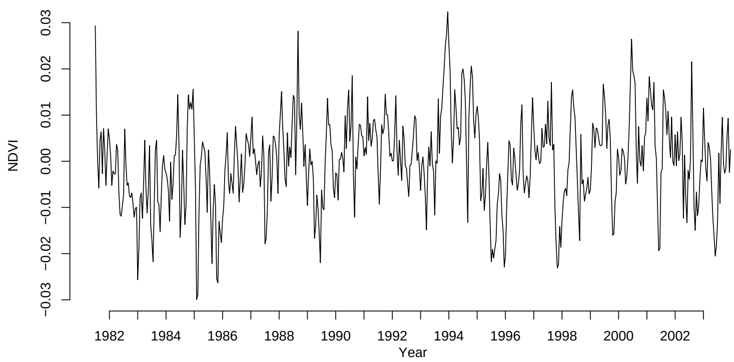
where $x(i)$ was the ith NPP value, x_{ave} was the mean value throughout the whole time series (Telesca et al. 2006). The processed data was then divided into several boxes, each with n data points. For each box of length n, a least-square fit was conducted, generating straight lines whose y coordinate was denoted by $y_n(k)$. Next, the integrated time series $y(k)$ was detrended by subtracting the local trend $y_n(k)$ in each box. The root-mean-square fluctuation of this detrended time series was then calculated:

$$F(n) = \sqrt{\frac{1}{N}\sum_{k=1}^{N}[y(k) - y_n(k)]^2} \tag{4.9}$$

The calculation was then repeated for each box size n to provide the relationship between $F(n)$ and n. In analysis, $F(n)$ and n are often plotted onto a log-log graph and if scaling is present will appear as a straight line. The slope of this line is the scaling exponent α. The value of α at a certain point $\log n$ indicate different relationships between NPP values in the box of size n and a previous box's values. Different values of α and their meanings are summarised in Table 4.2.



(a)



(b)

Figure 4.2: Time series of (a) NDVI average value in Northern Tibet and (b) fluctuation over seasonal average trend obtained by removing seasonal average NDVI value from original data.

On a computer, the NPP time series without seasonality trend were exported to a file and sent into the DFA program developed by Goldberger et al. (2000). The output file had two columns of data, which were the 10-based logarithms of "box size" and "fluctuation" in DFA. Plotting the

Table 4.2: Slope of fluctuation-time scale line and the corresponding time-series' characteristics (Peng et al. 1994)

α	Meaning
$< 1/2$	Anti-correlated
$\simeq 1/2$	uncorrelated
$> 1/2$ but < 1	correlated
$\simeq 1$	1/f noise
> 1	non-stationary, random-walk like
$\simeq 3/2$	Brownian noise

second column against the first one, a straight line could be obtained if the original time-series had self-affinity, i.e. remained the same when viewed at different scale (Freeman and Watkins 2002). Many natural time-series can generate points in the fluctuation-time scale plane that are close to collinear. The slope (α) of the fitted line can help researchers identify correlation of signal in the time series (Chen et al. 2002).

4.4.2 Persistence of NPP anomaly

The persistence here means for how long a positive or negative trend exists in a time series. In order to find out at what time scale the disturbances affect the grassland vegetation, a persistence probability approach was employed. The approach was proposed by Simoniello et al. (2008). The idea was to find out at what locations the positive or negative trend of NDVI relative to a certain reference persists, and if it persists how long was the lifespan of the trend. The actual quantity difference between NDVI and the reference value was ignored.

The approach was adopted in this study but the NPP anomaly was used instead of NDVI, because NPP anomaly had incorporated temperature and water availability, and thus can better reflect grassland status. To calculate the persistence over a period, the NPP anomaly data in the initial year t_i was transformed using the following rule:

$$s(x,y,t_i)=\begin{cases}1, & \text{if} \quad n(x,y,t_i)>0 \\ -1, & \text{if} \quad n(x,y,t_i)<0 \\ 0 & \text{if} \quad n(x,y,t_i)=0\end{cases} \tag{4.10}$$

where $s(x,y,t_i)$ is the transformed value at pixel (x,y), $n(x,y,t_i)$ is the original NPP anomaly value. After such transformation only the sign of original data was preserved. Then for each year t afterwards ($t \geq t_i$) the persistence map $P(x,y,t)$ was constructed as follows:

$$P(x,y,t) = s(x,y,t) \quad t=t_i \tag{4.11}$$

$$P(x,y,t) = \begin{cases}0, & \text{if} \quad s(x,y,t)\neq P(x,y,t-1) \\ P(x,y,t-1) & \text{if} \quad s(x,y,t)=P(x,y,t-1) \quad t>t_i\end{cases} \tag{4.12}$$

At each year T a cumulative value for each pixel could be obtained:

$$P_{t_i}^{T}(x,y)=\sum_{t=t_i}^{T} P(x,y,t) \tag{4.13}$$

This value indicated for how many years in the period in question the NPP trend had persisted at the pixel and its sign indicates whether the trend was positive or negative. If $||P_{t_i}^{T}||$ was high, it meant there were many consecutive years in which the NPP was higher or lower than average. But if NPP fluctuates around the average, $||P_{t_i}^{T}||$ would be low. The sign of $P_{t_i}^{T}$ indicated whether positive or negative trend dominated in the period. In Simoniello's approach the last step was to calculate the probability of the trend's survival:

$$q(t)=\frac{N(t)}{N(t_i)} \tag{4.14}$$

where $N(t)$ is the number of survived trends having the same sign at the time t. But arguably the result of this equation was an indicator of stability rather than resilience. This study instead examined $P_{t_i}^{T}(x, y)$'s value and spatial distribution as well as its change through time, in order to identify which areas tend to have positive or negative trend in a given period and whether these characteristics changed through time.

In order to compare long-term and short-term persistence of NPP trends, various reference years and time spans were selected: 22 years from 1982 to 2003, using all available images, to obtain a whole picture from all available data; 10 years from 1982 to 1991 and 1992 to 2001 respectively to compare the two halves of the period; 5 years from 1982 to 1986, 1987 to 1991, 1992 to 1997 and 1997 to 2001 to examine trends at a finer scale; and 3 years from 1984 to 1986, 1991 to 1993, and 1997 to 1999, which were beginnings of 3 El Niño periods, to examine whether El Niño events influence NPP trends.

4.5 Conceptual and mathematical model

Resilience is an holistic attribute of the system and in most cases cannot be measured directly. The assessment of resilience has to rely on some surrogates that can be measured using conventional means. In order to identify these surrogates, a conceptual model is often required so as to identify important components and interactions, whose attributes or quantities can serve as surrogates. On the other hand, resilience studies look not only at the system's history, but more importantly at future surprise and adaptation. Therefore, mathematical models are often used to illustrate the system's behaviour and changes in attributes in resilience studies.

4.5.1 Development of conceptual model

The conceptual model of the Tibetan grassland system was drawn from the researcher's understanding gained in his field study in 2003 to 2005 (see Section 4.1.2) of the pastoral system, including key components and seasonality features, shown in Figure 4.3. In this model, grass productivity and availability were chosen as the core attributes of the system, which is a major limiting factor of the availability of livestock, which in turn supported pastoral population and economy. The core factors were influenced by these factors:

- Grazing intensity (not shown in the figure), which is determined by the number and composition of livestock, as well as the area of pastures available to the herd. Observations by Wu et al. (2004) in Tibet shows that heavy grazing increases the density of plants, but decreases community height, coverage and biomass, i.e. the individual plants are shorter and smaller with less leaf area.

- Growth and recruitment of grass, affected by net primary productivity and the viability of seed banks. The net primary productivity is determined by various climatic factors such as available solar radiance, the ratio of radiance that can be utilised by the vegetation, temperature and water availability. The availability and viability of seed banks were reported to be dependent on altitude and soil microtopographies (Isselin-Nondedeu and Bédécarrats 2007).

- Topography and hydrology. The topography of grassland determines how much solar radiation and precipitation the vegetation receives. It also directly influences the flow of soil water content in the soil and evapotranspiration. Soil erosion is also linked to topography.

- Disturbance, such as snowstorm, drought and fire. Snowstorms are a frequent weather phenomenon in Tibet, defined by heavy snowfall, prolonged snow cover period and greater depth of snow than usual (Zhu et al. 1999). Snowstorms can take place in autumn, winter or early spring in the year. Small snowstorms take place almost every year although in different locations in Tibet. Larger snowstorms appear less frequently, but affect larger areas when they take place. Among snowstorms, those that take place in spring are considered most harmful, as they delay or prevent grass from germinating, and cause shortage of food for livestock, which are often weak after the long winter and in need of abundant herbage. The occurrence and intensity of snowstorm disasters are linked to the interaction between Indian Summer Monsoon and the Westerlies. Drought is considered as a common feature of the Tibetan Plateau (Yang et al. 2004). Its occurrence is also linked to weakened monsoon and abnormal seasonal distribution of precipitation. The trend of global climate change is believed to be making droughts more frequent (Smit and Cai 1996/7).

- Wildlife influences the availability of grass communities. The microhabitat disturbance created by some wildlife species is believed to increase plant diversity on the grassland (Smith and Foggin 1999). Wildlife also provide necessary tools such as antelope horns (used as a container when milking sheep and goat) and serve as an indicator of favourable pasture conditions, telling herdsmen where to move the livestock to (Foggin 2005).

- As a social-economic-ecological complex system, the viability of the system, represented by productivity, is also influenced by human interactions and policies. Land use patterns, although not a major factor in Tibet's pastoral productivity now, will play a more important role in determining the productivity and consumption of the grassland, as the urban areas expand and road network develops. Local and national economy have an impact on the demand of pastoral products and people's income. Local people's livelihood influences their impact on local environment and their ability to survive adverse changes. The political effectiveness and fairness contribute to the implementation of policies, and therefore the impact of human introduced changes.

- Finally, the mobility of herds and pastoralists is linked to many aspects of pastoralism and grassland ecosystem. As the landscape is very challenging, local people rely on the mobility of livestock to obtain forage from grassland and shrubland. The optimised use of pastures is difficult to achieve without a certain degree of mobility (Richard 2003*a*). Mobility of a multi-species herd has been considered as crucial to the survival and sustainability of Tibetan pastoralism (Congressional-Executive Commission on China 2004).

By the spatial and temporal scales at which these factors exist, they can be categorised into three types: small-scale, fast changing factors; large-scale, slowly changing factors; and cross-scale factors. The fast factors include disasters such as snowstorm, drought and fire, as well as livestock population and soil erosion. These factors' impact are limited to a specific locale and a period, some can easily be controlled by management. Slowly changing factors include seed bank, biodiversity, climate, human population, social effectiveness and fairness, and topography. At a larger scale, these factors' change is only perceivable in the long term, despite small fluctuations in some specific locations. Finally, cross-scale factors such as temperature, precipitation, soil nutrient, and grass availability. can interact with both fast and slowly changing variable, and have different behaviours at small and large scales.

Accordingly, the interaction between these factors can be classified into within- and cross-scale interactions as well. Within-scale interactions' impact is limited to the same scale as the subject. Cross-scale interactions are those in which small-scale process influence a large-scale attribute, or vice versa. An example of within-scale interaction is that between grazing and biodiversity. Grazing intensity influence the dominant species in the community as well as the species diversity index, but the influence is not linear. In different seasons, the impact of grazing on biodiversity is different (Wu et al. 2004). Some herbivore wildlife species, such as Tibetan ass, may compete with livestock for herbage, while carnivore species such as wolf and bear attack livestock and other herbivores and reduce their numbers (Yangzong 2006). Examples of cross-scale interaction include the impact of water availability on livestock population, and drought on fire occurrence. Some of these interactions are cross-scale because of the flow of mass, energy, or people.

Some elements in the model have both positive and negative interactions among them. For example, livestock limit the growth of edible grass by foraging, but at the same time they also improve the nutrient in the soil and help grass seeds' propagation. Similarly, rodents on the grasslands feed on grass and damage soil in some areas, but they also create microhabitat disturbances that increase plant species richness (Smith and Foggin 1999). These interactions usually involves other entities in the system therefore they are not usually presented as complex interaction between two entities but an interaction network with three or more nodes. In the mathematical model derived from the conceptual model however, these complex actions were expressed as both positive and negative terms in a certain entity's function.

4.5.2 Key functions and attributes

The key functions of grassland ecosystem can be defined in two categories: ecological functions and social-economic functions. The definition of eco-

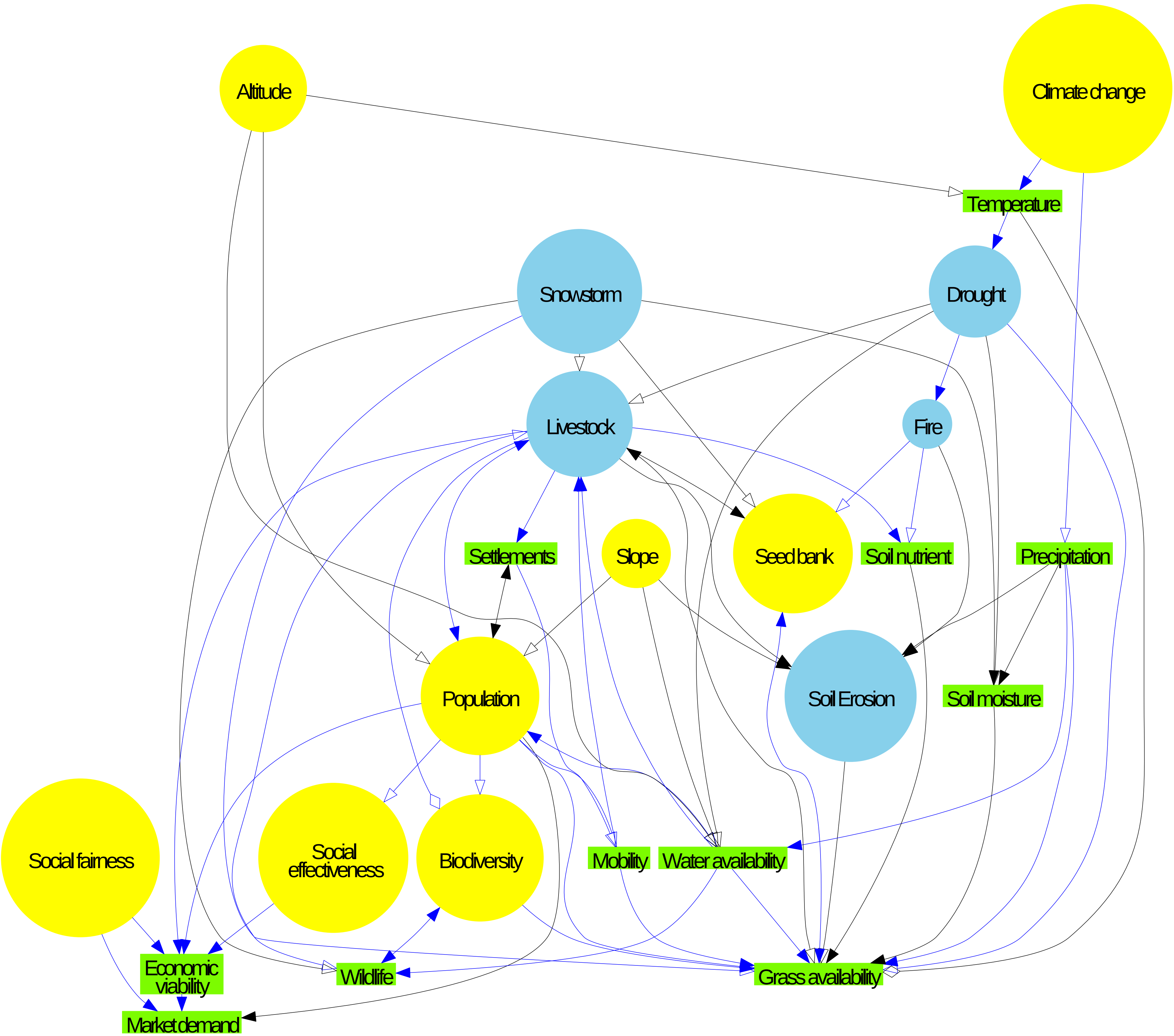


Figure 4.3: Conceptual model of Tibetan pastoral system. Yellow circles denote slowly changing components; green rectangles denote cross-scale components; blue circles denote fast changing components. Black arrows are within-scale interactions while blue ones are cross-scale. Filled arrowhead denotes positive impact, empty arrowhead negative impact, and empty diamond denotes both positive and negative impacts combined. The size of circles and boxes have no meaning other than serving layout purposes.

logical functions depends more on the location, organisation and surrounding environment of the system being studied. The site-specific functions are often given more weight when considering the key ecological functions as they are usually defining the system's unique identity. The Tibetan grassland ecosystems supports a range of endemic species due to its high-altitude, low-temperature and semi-arid environment. The vegetation creates and maintains a thin layer of soil that is vital for the existence of grassland ecology. In the rivers' source area, the presence of vegetation and soil structure also preserve water enabling year-round flow. These are the key ecological functions of the system.

The key social-economic functions of the Tibetan grassland system depends on the aim of the system's management. For the past one thousand years or so the purpose of pastoral system in this area has been supporting a population's survival, but since the mid-20th century it has gradually changed to economy development and the improvement of local living standard. It is said that Tibetan pastoralists are being transformed into ranch livestock producers (Miller 1999*a*). Therefore, the social-economic function of the system has to shift from supporting subsistence only to supporting both subsistence and a livestock community that has surplus for export and trade. Moreover, the state has set the sustainability goal for the area, thus the production of the system should meet the demands of economic development without rendering uncontrolled environmental-damaging activities such as mining necessary or even favourable.

The attributes of the system should support these functions. One of the most important attributes is the climate of this area. While endemic species such as yak (*Bos grunniens*) cannot survive in warmer climate conditions, the more important climatic attribute is the ability of high altitude, low temperature areas to retain glaciers thus vital water supply. More specifically, the key attributes include temperature and precipitation patterns, evapotranspiration, and the influence of monsoon and westerlies system. Another important attribute is the steppe and meadow soil. The organic matter in the soil is not only an irreplaceable source of nutrient for vegetation but also a sink of organic carbon (Wang et al. 2002). The permafrost layer is also critical to the hydrology of the grassland. The productivity of grass and the number and turnover of livestock are the most direct attributes representing the system's function.

The social-economic attributes that are important for the system's resilience include local people's relationship with their land and their effort in conservation. For an large economic system to function properly, the openness of market and transparency of price is essential. The population and economic policies can enhance or dampen the competitiveness of the local economy and products, thus are parts of the system's key attributes.

The notion of cross-scale interactions in the conceptual model provides another means of identifying key attributes and processes. Cross-scale interactions generate non-linear behaviours which often result in surprises. Using this criterion, grass availability, livestock population, and human population are probably the attributes most worth examining in the system.

4.5.3 Temporal and spatial scope and scale/granularity of the model

The establishment of the model's temporal and spatial scope requires consideration of both natural and social processes. Some natural processes such as regeneration of grass are relatively rapid and can be directly incorporated into the same framework as social interactions, but most natural processes take place over a longer period that exceeds the general time frame of management, such as the accumulation of seed bank and desiccation of grassland. Moreover, some natural processes occur periodically, typically with an seasonal or annual pattern, while the society's adaptation may take generations of time. The effects of policies may be expected in a well-defined area but may also diffuse to adjacent areas, while the impact areas of natural interactions are much harder to define. Such complexity, along with extensive cross-scale interactions in the system, render it necessary to define the optimal scope and scale of the model.

Another consideration was the availability of data. Most remote sensing data used in the study were available in the form of monthly or fortnightly aggregated images, which provide a reasonable temporal resolution for most of natural phenomena. Nevertheless the census data available generally are annual. Similarly, the herd and pastoral family are the desirable unit in terms of studying their interaction with the grassland, but their effects on grassland were often aggregated to the prefecture level in official statistics.

Based on these conditions, the time step of the model was chosen as a year, with consideration of seasonal variation of livestock and vegetation. The minimum temporal granularity was chosen as a month, due to the availability of remote sensing data, which allows phenomena such as late germination or abnormal snow patterns to be identified via NDVI. In terms of spatial granularity, the model attempted to model a typical pastoral family with 5 people and 105 standardised sheep units (one sheep unit equals to one sheep or one goat or one fifth of a yak (Yan et al. 2005)), and their management and impact on the allocated grassland. The estimation of typical family's livestock number was based on the census data from 2006 and 2007 (Yao 2007, Takung Pao website 2007).

The spatial scope was mainly Northern and Western Tibet, south of Thangula Mountains and north of Niangqien Thanglha Mountains. The pastoralism in these areas follow similar scheme due to comparable climate conditions and are different from the sedentary agro-pastoralism in the southern low-altitude areas. The temporal scope was set to 50 years in the future, assuming global climate change is causing retreat of glaciers and degradation of permafrost as well as altered temperature and precipitation patterns. A longer simulation period for the model is desirable but difficult to achieve as more uncertainty may be introduced in the long term.

4.5.4 Model of Tibetan grassland

From the conceptual model and key attributes identified it was decided to use grass availability and livestock population as surrogates of resilience. The rationale for choosing them included their key role in the grassland social-ecological system and supporting local populations, as well as the relative easiness of obtaining data from remotely-sensed images and utilises existing model.

The model was based on other grassland dynamic models. The high altitude meadows and steppes on the Tibetan Plateau are adapted to the short growth season, limited water availability and unequal precipitation. Many other grassland/rangeland models consider the competition between shrub or other woody plant and grass, but due to the unique grassland environment in Tibet determined by high altitude and short growth seasons, such competition has a very limited spatial context. Besides, unlike savannahs or Australia ranches, the dominant shrub species Bush Cinquefoil (*Potentilla fruticosa*) is edible by the livestock and provides summer grazing food (Klein et al. 2007), although shrub competition could be used as an indicator of desertification (Li et al. 2006). The major interacting factors in the model included grazing, disasters and occasional fire.

The model was relatively simple in that it simulates the growth of grass and shrub without addressing the underlying drivers of vegetation growth, such as soil moisture content and the physiology of various grass and shrub species. This was due to the practical difficulty in obtaining these data. On the other hand, for a fully parameterised vegetation dynamic model, the parameters valid for one location often cannot be applied to another, thus the application of these models in Tibet's environment would be extremely time-consuming, if meeting the data requirement was possible. Instead, the model focuses on aspects that can be measured by remote sensing, and was parameterised from remote sensing observations and other published measurements or statistics. The model contained grass and shrub growth functions based on intra- and interspecies competition as well as randomly generated disturbance driving changes. Below is a description of model construction process.

In areas with shrub competition, the rate of change of grass density was expressed as (Ludwig et al. 2002).

$$\frac{dg}{dt} = r_g g(1 - s - c_{gg} g - c_{wg} w) \tag{4.15}$$

where g is the grass density, w the woody plant density. r_g is relative growth rate, and c_{gg} and c_{wg} are competition coefficients of grass's intra-species competition and shrub-grass competition. The parameter s was determined by grazing intensity (see Equation (4.31). The rate of woody plant growth was represented by equation

$$\frac{dw}{dt} = r_w[a + w(1 - c_{gw} g - c_{ww} w)] \tag{4.16}$$

where r_w is relative growth rate, c_{gw} and c_{ww} are competition coefficients, and a is a source term, i.e. newly introduced vegetation.

The fire risk was estimated by modelling the fuel availability. First, the grass production is given as

$$g_p = r_g g + a_g \tag{4.17}$$

where a_g is a source term, while r_g is the rate of grass production available for grazing. The grass not consumed by grazing can be potential fuel, denoted by g_f, thus

$$g_f = g_p(1-s) \tag{4.18}$$

Equation (4.15) was therefore replaced by equation (4.19).

$$\frac{dg}{dt} = g_f - g_p(c_{gg}g + c_{wg}w) \tag{4.19}$$

The age of woody plants influence their susceptibility to fire. Introducing a new variable h denoting the product of the woody plants density and the average age of the woody plants, the dynamics of w and h could be represented as

$$\frac{dw}{dt} = r_w w(1 - c_{gw}w - c_{ww}w - s) - fw + a_w \tag{4.20}$$

$$\frac{dh}{dt} = w - r_f f h \tag{4.21}$$

The fire risk f was defined by a fire potential p which is proportional to the available fuel:

$$p = \begin{cases} c_f g_f & \text{if } h > 20 \\ c_f g_f h/20 & \text{otherwise} \end{cases} \tag{4.22}$$

$$f = p\frac{h^\alpha}{(wa_0)^\alpha + h^\alpha} \tag{4.23}$$

where a_0 is an age at which the fire risk is about a half of its maximum, the parameter α determines the steepness of the increase of fire risk with age.

In Tibetan Plateau's context, however, the age structure of woody vegetation is not clear. The growth of the dominant shrub species Bush Cinquefoil (*Potentilla fruticosa*) and its ability to provide fuel does not vary with its age, therefore only the first case in equation (4.22) was used, i.e. $p = c_f g_f$, which can be further simplified as $p = c_f g$, by incorporating the proportion of fuel in grass biomass in c_f. Fire risk f was thus not a function of average age h, but a function of p. Because growth of grass is also affected by fire, equation (4.19) was further modified as

$$\frac{dg}{dt} = g_f - g_p(c_{gg} g + c_{wg} w) - c_f g \times g \tag{4.24}$$

Grassland vegetation also faces climatic disturbance such as snowstorms. For the specific spatial scale of the modelling, climate events do not impact a household or a prefecture every year, but are presented as stochastic events. On a larger spatial perspective, significant climatic disturbances do take place almost every year. The effects of these disturbances include both short-term and long-term ones. In the short term grass is covered or destroyed and the population of livestock is reduced due to lack of forage; in the longer term these disturbances reduce the availability and viability of the seed bank as well as the ability of the herd to reproduce and recover. In order to incorporate disturbances into the grassland model, variables e_g, e_w and e_l were defined, which denote the impact of disturbances on the source term of grass and shrub, and on grazing intensity (livestock numbers), respectively. When both grass and shrub are available, livestock will forage both, and the ratio of shrub and grass in the forage is assumed to be equal to the ratio of shrub and grass available. The disturbance on grass will influence its availability, and livestock will turn to shrub as an alternative source of forage. Therefore equation (4.19) and (4.20) can be written as

$$\frac{dg}{dt} = (r_g g + a_g) \times [1 - s \times \frac{g}{w+g} + e_l - e_g] - (r_g g + a_g)(c_{gg} g + c_{wg} w) - c_f g^2 \tag{4.25}$$

$$\frac{dw}{dt} = r_w w[1 - s \times \frac{w}{w+g} - c_{gw} g - c_{ww} w - (e_g - e_l)] \\ - g \times c_f g_f w + (a_w - r_w w \times e_w), \quad e_l < s \quad (4.26)$$

The impact of disturbance itself was a decaying function of time. Adopting nomadic or sedentary pastoralism has different influences on the function. For nomadic pastoralism the possibility of encountering a short term disturbance such as a snowstorm is greater, and it takes less time to recover from such disturbance due to more balanced livestock sex ratio. In comparison, sedentary pastoralism is more susceptible to long term disturbances of resources, such as drought. Both schemes may take considerable time to recover from long term disturbances. Thus the equations for e_g, e_w and e_l were formulated as

$$e_{g,w,l} = e_i \exp[c_e(1-t)], \quad t \geq 1, \quad c_e > 0 \quad (4.27)$$

$$e_{i+1} = e_{g,w,l} + e_i \quad (4.28)$$

$$c_{e_{i+1}} = c_e \times \exp(-1) \quad (4.29)$$

where e_0 is the initial impact, c_e is a parameter determining the speed of recovery from the impact, with a small value denoting slow recovery or long term impact. The reason to use an exponent in both equation (4.27) and (4.29) was because the basic pattern of a disturbed population's recover and the time series of disturbance often follow a exponential decay pattern (e.g. Douglas and Trustrum 1986, Berryman 1999). A new disturbance can be superimposed on an existing, not fully recovered disturbance, as equation (4.27) shows. In this case the impact was equal to the initial impact of the new disturbance plus the remaining impact of the previous disturbance; the recovery coefficient to $1/e$ of that of the previous disturbance.

In order to simulate the occurrence of disturbance, whether $e_{g,w,l}$ was added into the equation was determined by a simple probability test. Due to the fact that El Niño events impact the area every 2 – 5 years, and snowstorms strike almost every other year, the probability of a disturbance taking place in a year was set to 0.5 for a nomadic system, and 0.3 for a sedentary system. Therefore, the total number of disturbance in a given time series followed a binomial distribution.

The initial intensity of each disturbance $e_{i_{g,w,l}}$ was following a distribution known as the generalised extreme value (GEV), whose cumulative distribution function is written as (Katz et al. 2005):

$$F(e_i;\mu,\sigma,\xi) = \begin{cases} exp\{-[1+\xi(e_i-\mu)/\sigma]^{-1/\xi}\}, & 1+\xi(x-\mu)/\sigma > 0 \quad \xi \neq 0 \\ exp\{-exp[-(e_i-\mu)/\sigma]\} & \xi = 0 \end{cases} \tag{4.30}$$

The value of μ, like its counterpart in a normal distribution, tells where the distribution is "centred", and σ tells how the distribution "spread". The sign of ξ determines the shape of the curve of cumulative distribution function. As environmental fluctuations are best described by the $1/f$ "pink" noise pattern while their frequency and intensity follows a power-law relationship (Halley 1996), the case that $\xi > 0$ was considered as a more plausible distribution in this study. Equation (4.30) therefore yielded a heavy-tailed (Frèchet) distribution. As the DFA analysis (see section 4.4.1) showed that the system was dominated by positive feedback and greater disturbance tend to take place after a previous disturbance, a uniformly distributed random variable whose range was determined by time t was added to e_i to simulate possible greater disturbance.

The growth rate of grass (r_g) was estimated by calculating the ratio of annual dry matter production (4.0 t/ha/a) to the total grass biomass measured by dry matter in the area (40 – 48 t/ha/a)(Dong et al. 2003, Fan et al. 2008), which gave r_g = 0.083 – 0.1. The growth rate of shrubs r_w was estimated similarly, using data from Luo et al. (2002), which yielded r_w = 0.11 – 0.31.

At present the TAR has livestock equal to 50 million standard sheep units, distributed over pastures with an area of 80 million ha. However, the actual load on the grassland is usually higher due to the unbalanced distribution of pastures and livestock. The actual typical load is about 5 standard sheep units per hectare. Dong et al. (2003) suggested that 6.0 – 7.0 t dry matter each year was needed to support a stocking rate at 20 – 25 standard sheep units, thus on average 1.5 t dry matter was needed to support the average stocking rate, this gave a grazing intensity of

$$s = 1.5/4.0 = 0.38 \tag{4.31}$$

The source term a could not be determined from available data, which contains no information on the probability of seed production, propagation and establishment. Therefore a_g and a_w were considered as part of r_g and r_w respectively and not explicitly incorporated in the model. This is justified by the fact that r_g and r_w are measured in controlled conditions (no grazing), and the model does not consider propagation from other locations, thus r_g and r_w can be considered as representing all growth of vegetation. The competition coefficient used the suggested value in Gunderson and Pritchard (2002) and Janssen et al. (2000), reduced to suit r_g given above, which gave $c_{wg} = 0.16$, $c_{gw} = 0.16$, $c_{gg} = 0.2$, and $c_{ww} = 0.2$. Because the actual r_g, r_w, and c values were not clear in the case of the Tibetan Plateau, it had to be assumed that a null model existed, in which the abundance of both grass and shrubs were approximately constant. By searching for the null model the suitable parameter set could be found.

The coefficients for the disturbance model were determined arbitrarily. A series of $e_{g,w,l}$ values ranging from 0.2 to 0.8 were tested, as well as

c_e values from 0.1 to 2. The fire risk c_f was set to 0.4 in Gunderson and Pritchard (2002), but was set to 0 in this simulation to reflect the ignorable fire risk of grassland due to lack of fuel on the Tibetan Plateau (Miehe et al. 2009). The parameters of the probability of disturbance were set to $\mu = 1$, $\sigma = 0.25$, $\xi = 0.1$ to simulate the distribution of disturbance, in which larger disturbance is rarer.

The model's computational implementation was carried out in R language, which is similar to the S language developed by Bell Laboratories (R Development Core Team 2008). There were three functions, one of which read data from a ASCII file, another ran the model simulation, and a third introduce stochastic disturbances.

The input file had two columns. The first was the names of parameters, merely for the sake of readability; the second contained corresponding values of these parameters. The two columns were separated by a character such as a space or a comma. By changing the values in the input file, different settings, or scenarios, with differing competition level, disturbance intensity and probability were simulated. The detailed R script and input file format can be found in the appendix A.

A series of possible situations and scenarios were then defined to find out how the system's grass productivity and resilience change with the resource availability, adaptability, composition and institutions of the system. The scenarios included:

- After 20 years of nomadic practice, the system is transformed into a ranch-based system similar to that in Australia; then the new system continues to operate for 130 years. In and after the transition the recovery rate for vegetation and livestock decreases while the probability of disturbance becomes smaller, i.e. the system is less likely to encounter disturbances and less likely to recover in a short period, as discussed earlier. The grazing intensity is also higher in the ranch-based system.

- Climate change causes the system's rate of recovery to drop and the probability of fire and other disturbance to increase. The diminishing permanent frost layer causes the water availability to reduce, therefore the growth rate and vegetation availability drops.
- The urbanisation in some areas leads to less pastoral management in the system, the grazing intensity is reduced as well as the availability of grass.
- The combined effect of the scenarios above.
- Changed competition coefficient for grass and woody plants.
- Changed composition of grass and shrub.
- Increased population causing constantly increasing grazing intensity; while the system is employing ranching practice.

The scenarios were built based on the trend of population increase and warmer, drier climate projection (Niu et al. 2004, Du et al. 2004). In ranching practice the system is managed to optimise the production of grass, thus the competition coefficient and the composition of grass and shrub will change.

The construction of the model was a derivation of a model based on Australian rangeland (Ludwig et al. 2002), which has similar ecology aspect to that of Tibet but a different management system. Thus the model might not reflect actual grass/shrub and grazing dynamics on the Tibetan Plateau. Therefore a few altered constructions of the model were attempted, to examine some possible results of the plateau's unique ecotone composition and grazing management practice. These alterations of the model involved changes in the model mechanism, or the parameter set. The alterations attempted included:

1. Absolute grazing intensity is a constant value instead of being proportional to grass and shrub availability.
2. The initial abundance of either grass or shrub is 0.
3. There is no interspecies competition as both grass and shrub species occupy their own optimum niche which is not possible for other plant species to establish.
4. The number of livestock is kept constant.

4.6 Spatialisation of the model

In order to explore more mechanics behind the dynamics of grazing and vegetation, the model was further developed by adding spatial dimensions into the design. The addition allowed the researcher to study the impact of spatial heterogeneity and the spatial processes. The model was reconstructed by allocating parameter values to raster maps of the area, while the calculation involving individual parameters was now carried out with matrix calculations.

4.6.1 Construction of parameter rasters

The parameter rasters required in the model were identified according to the dynamic model described in Section 4.5.4, based on the map of vegetation types in the area. The matrices required by the model included:

- Matrices of abundances of grass and shrub;
- A matrix of stochastic disturbances;
- Grazing intensities;
- Intraspecies and interspecies competition;

- Rates of vegetation and livestock recovery from disturbances;
- Growth rates of grass and shrub;
- Landcover and Land use types;

The matrix of abundance of grass and shrub was constructed using landcover type data from Hansen et al. (2000). The landcover in this area can be categorised into 9 types: water (0), woodland (6), wooded grassland (7), closed shrubland (8), open shrubland (9), grassland (10), cropland (11), bare ground (12), and urban/built (13). For each type a initial abundance of grass and shrub is set as in Table 4.3.

Table 4.3: The initial grass and shrub abundance value allocated to various land cover types

Code	Type	Grass abundance	Shrub abundance
0	Water	0	0
6	Woodland	0.1	0.5
7	Wooded grassland	0.5	0.5
8	Closed shrubland	0	1
9	Open shrubland	0.5	1
10	Grassland	1	0.3
11	Cropland	0.1	0.1
12	Bare ground	0.1	0.1
13	Urban/built	0	0

The matrix of disturbance was generated by randomly selecting the locations where disturbances take place. The other stochastic characteristics of the disturbances was determined by probability distribution similar to that described in Section 4.5.4. The parameters of the disturbance distribution, including the probability that a disturbance take place, the rate of recovery and the impact level of disturbances were determined for each land cover type and is summarised in Table 4.4. The level of disturbance was determined based on previous study of global disturbance and the characteristics of Tibetan vegetation types. The probability of disturbance was similar to the value used in the non-spatial model, with adjustment for each land cover type. The intensity of disturbance of livestock was set to 0.1 for the whole area.

Table 4.4: Disturbance model parameters by land cover types

Code	Type	Global disturbed fraction[1]	Adjusted disturbance level	Disturbance probability
0	Water	0	0	0
6	Woodland	0.12	0.2	0.2
7	Wooded grassland	0.13	0.2	0.2
8	Closed shrubland	0	0	0.3
9	Open shrub-land	0.08	0.1	0.3
10	Grassland	0.16	0.25	0.5
11	Cropland	0.17	0.3	0.2
12	Bare ground	0.27	0.4	0.5
13	Urban/built	0	0	0

[1] The value is derived from the result of Potter et al. (2003)'s study of global disturbance events for various land cover types.

The grazing intensity was set to be uniform (0.2) across various land-cover types, except for water, urban and cropland, which had no effective grazing. The intensity was set to be 50% higher near water sources, and in the case of ranching practice, 25% higher near urban areas and settlements. The level of interspecies competition by grass and by shrub, and intraspecies competition within grass and shrub, were denoted by c_{wg}, c_{gw}, c_{gg} and c_{ww}, and were set for each land cover type, shown in Table 4.5.

The rate at which vegetation recovers from disturbance was set to 1 in most areas, and 0.66 in areas with a north aspect. The numbers were only used to qualitatively reflect the impact of aspect. The rate of livestock's recovery was set to 1 for the area. The growth rate of grass and shrubs was based on that in the non-spatial model, modified by the standardised mode number of evapotranspiration level in this area, as higher evapotranspiration implies higher metabolism and growth rate. On top of

Table 4.5: Competition coefficients in different land cover types

Code	Type	c_{wg}	c_{gg}	c_{gw}	c_{ww}
0	Water	0	0	0	0
6	Woodland	0.3	0.1	0.1	0.3
7	Wooded grassland	0.2	0.2	0.2	0.2
8	Closed shrubland	0.3	0.1	0.1	0.3
9	Open shrubland	0.3	0.2	0.2	0.2
10	Grassland	0.1	0.2	0.3	0.3
11	Cropland	0	0	0	0
12	Bare ground	0.2	0.3	0.2	0.3
13	Urban/built	0	0	0	0

that, a layer of stochasticity was added to reflect the random fluctuation of growth rate.

The methods described in this chapter were employed to answer the important questions in a resilience study: the behaviour and state of the system in question, the pattern and trend of external disturbance, and how the system responds to the disturbance. The behaviour and state of the system were evaluated using NDVI and NPP as surrogates, as vegetation productivity is the most concerned attribute of the system; DFA and trend analysis were used to examine the pattern and trend of disturbance; the model attempts to simulate the interaction between the system and disturbance and find implications on resilience. The input to the model is not remote sensing data, but the characteristics of the data revealed by the other processes mentioned in previous sections.

Chapter 5

Results

5.1 Basic statistics

The NDVI values in some El Niño years show a downward change, e.g. 1987, 1991 and 1998 (Figure 5.1). although such change is not consistent in the whole time series, nor always significant compared to downward fluctuation in non-El Niño years. A graph of July NDVI time series shows correlation between NDVI and precipitation, although the fluctuation of precipitation seems to cause a lagged change (NDVI 1 year behind precipitation) of NDVI (Figure 5.2(a) and 5.3(a)). The NDVI values for August and September throughout the years shows similar relationship with temperature and precipitation (Figure 5.2(b) and 5.2(c)). As a result, the drier condition in El Niño years does not have a strong effect on NDVI, while warmer conditions in this area may be favourable to the growth of plants, thus increasing NDVI. However, in the coming year reduced temperature and the previous year's dry condition may cause NDVI to fall, which is more clearly shown in the scatter plots in Figure 5.3(b) and 5.3(c). It is worth noting that extremely high July temperature in previous year may be correlated to reduced NDVI in the following year, as shown in Figure 5.3(a), although the data points are not abundant enough to draw a significant correlation.

For northern Tibet subarea images, the time series of NDVI in shows that peak NDVI values often take place in August in each year. It is apparent that in El Niño years such as 1985 – 1986, 1991 – 1992, 1994 – 1995, and 1996 – 1997, the peak NDVI and growing season NDVI decreased. One-side T-tests show that the peak NDVI values in El Niño years are significantly smaller than those in non-El Niño years (p = 0.031). But growing season mean NDVI values do not have significant difference (p = 0.060).

The maximum NDVI value for each pixel throughout the whole time series (1981 – 2003) was derived from the data and presented in Figure 5.4(a); the maximum NDVI value minus actual NDVI value in an El Niño year generates Figure 5.4(b). A close examination of the two images reveals that in densely vegetated areas with higher NDVI value the impact of El Niño is also more manifested. The NDVI values in these areas may drop by as much as 80%, making them comparable to other areas with NDVI values around 0.1. In other areas NDVI values are also lower than the maximum potential value, but this does not hold true for all pixels when comparing the El Niño year's data with those of some of the non-El Niño years (Figure 5.5).

5.2 NDVI and NPP anomaly

From the $NDVI_\sigma$ map (Figure 5.6) it is apparent that in El Niño years both forest and grassland vegetation on the Tibetan Plateau shows negative anomaly, suggesting that El Niño is reducing plant growth from the year El Niño starts. In the following non-El Niño year the NDVI anomaly shows signs of recovery. However, such recovery is often replaced by negative anomaly again in the following year, such as in the year 1985

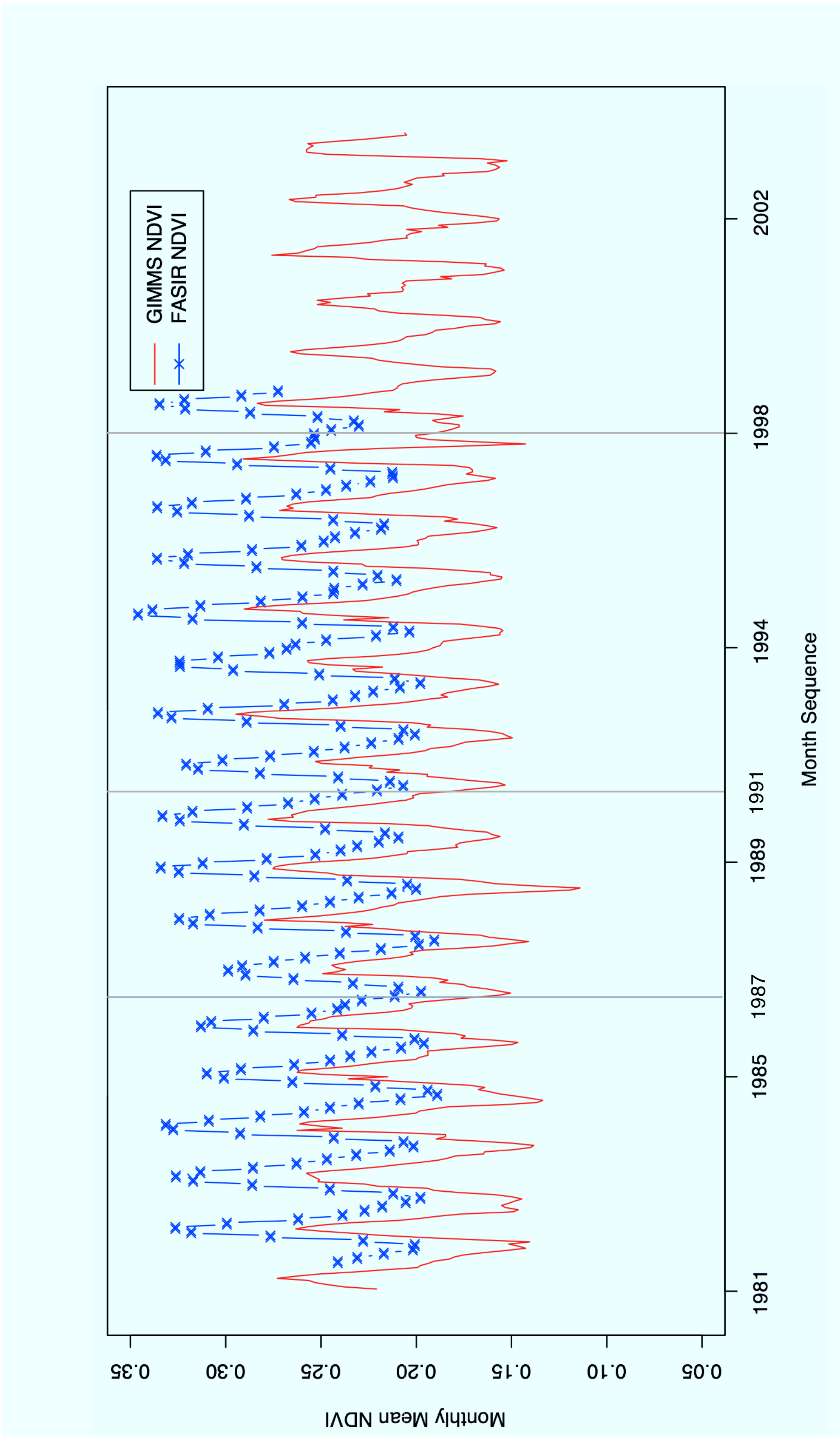
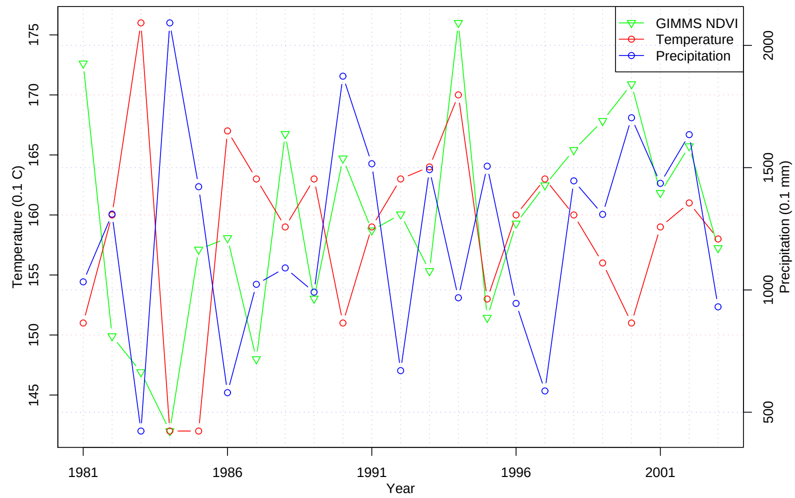
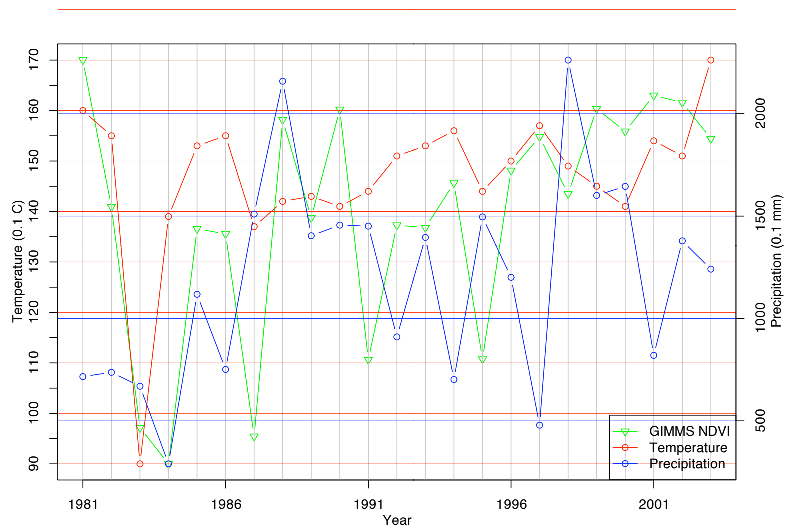


Figure 5.1: NDVI time series for Tibet and North India (75°– 105°E, 20°– 40°N). Temporal coverage of the data is from July 1981 to December 2003 for GIMMS, and January 1982 to December 1998 for FASIR. The year 1987, 1991 and 1998 are indicated by grey vertical lines.

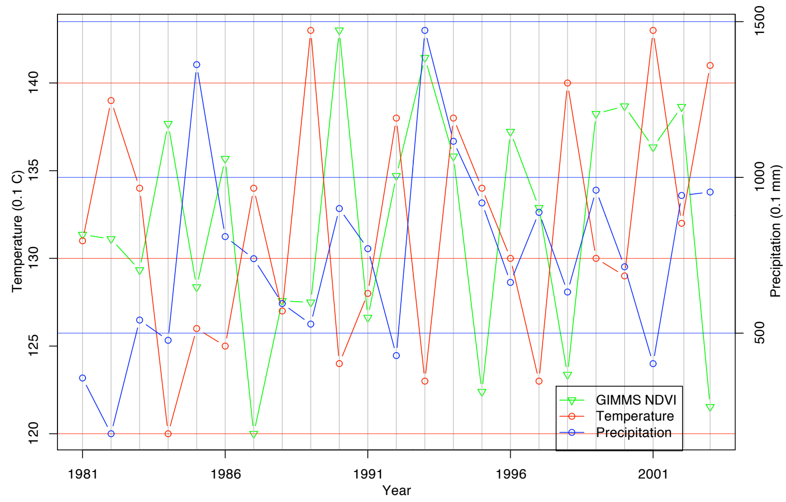


(a) July



(b) August

Figure 5.2: Temperature and precipitation observed in Lhasa and corresponding GIMMS NDVI value for the period 1981 – 2003

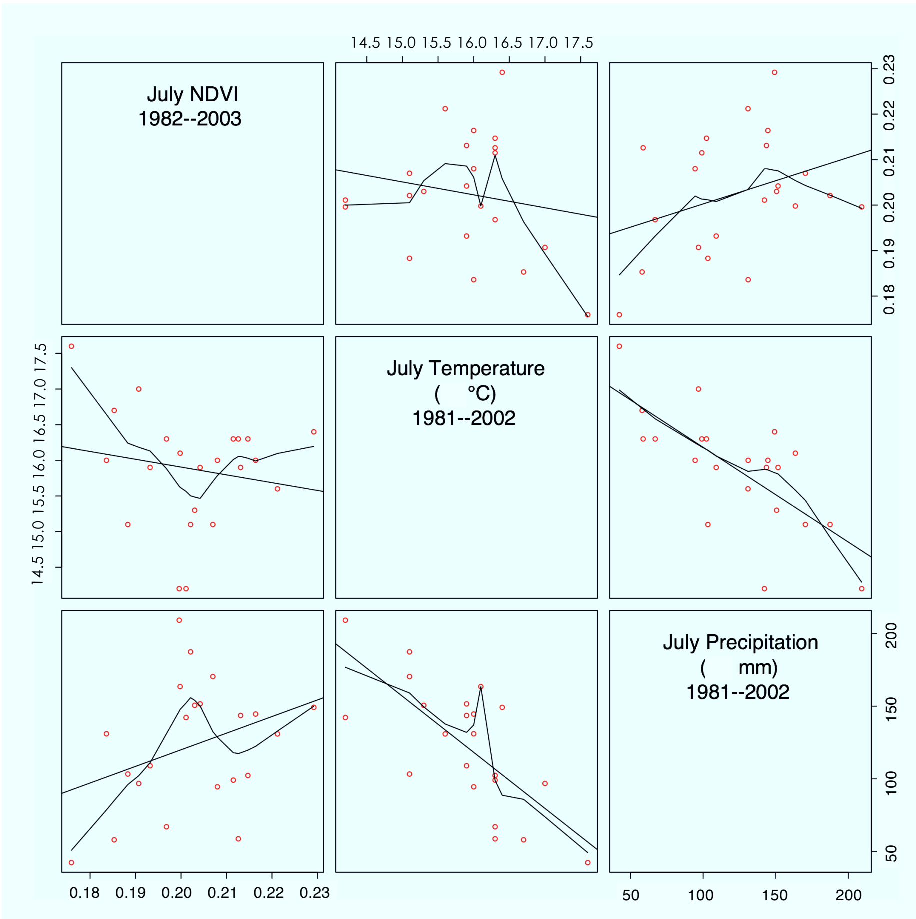


(c) September

Figure 5.2: Temperature and precipitation observed in Lhasa and corresponding GIMMS NDVI value for the period 1981 – 2003

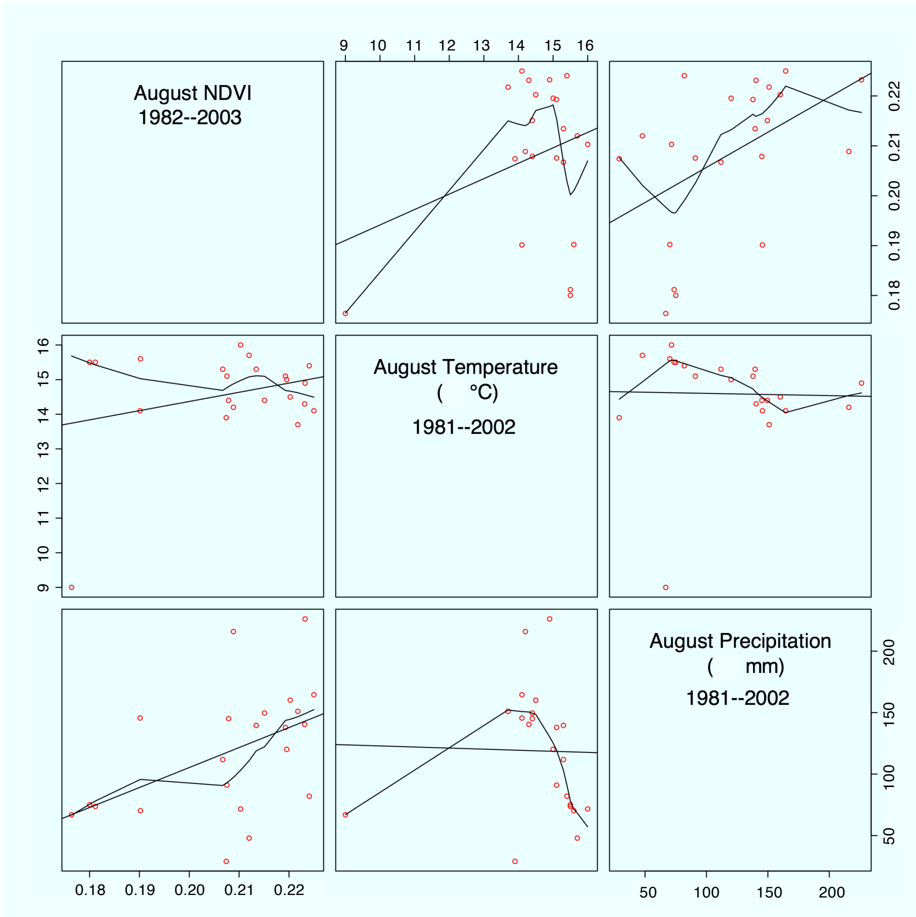
and 1989. In El Niño years in the eastern and southern part of the plateau NDVI anomalies are more significantly reduced. The negative anomaly tend to appear first in the east and south of the plateau. Whether this is because of the negative effect of El Niño on precipitation or reduced temperature after El Niño remains a question. But it should be noted that in 1998 and 1999 mean NDVI anomaly is still positive, which may be the effect of increased precipitation in 1998. NDVI values in growing season in El Niño years tend to decrease in the second year of the event, but may be mitigated by other factors, such as precipitation, for example, 1992, 1998 and 2002 are such years, see Figure 5.7.

Student's T-test shows no significant difference in the mean NDVI anomaly values in El Niño and non-El Niño years ($p = 0.61$). However, the north, south, east and west subarea images of growing season NDVI anomaly show that in El Niño years large areas of negative anomaly present. The comparison of anomaly in different years reveals that the change of anomaly from negative to positive and *vice versa* can be rapid and chaotic. An example is the changes from 1988 to 1990 in GIMMS time series (Fig-



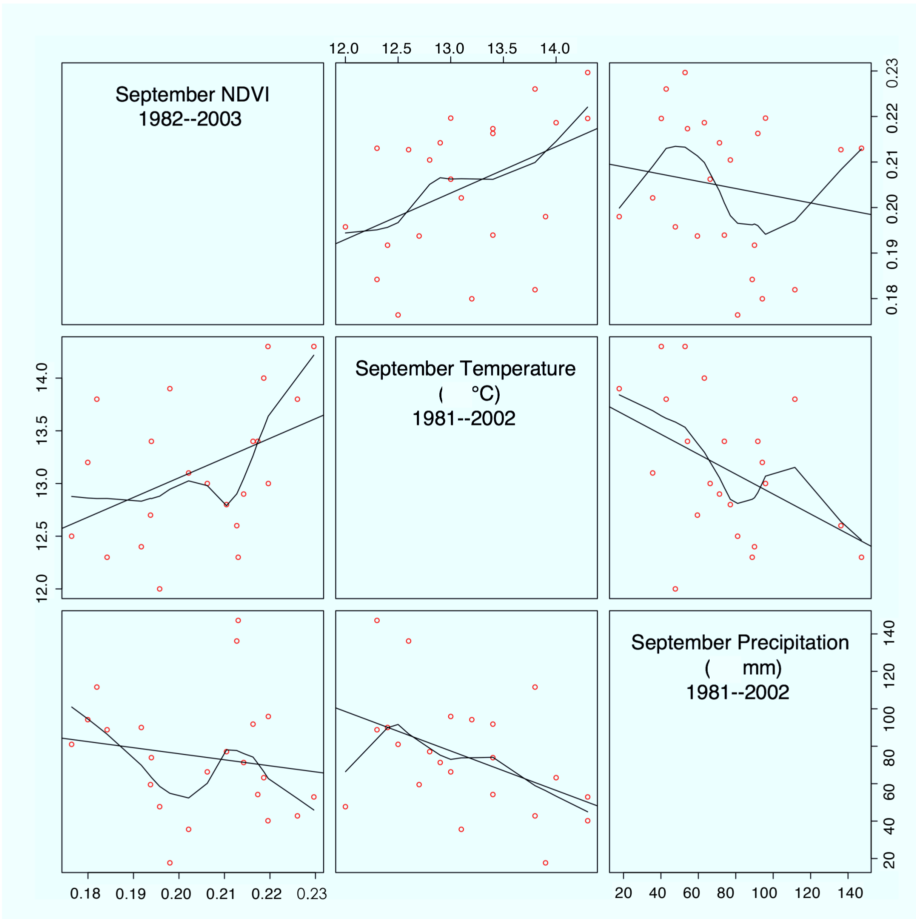
(a) July

Figure 5.3: Scatter plot matrix of average GIMMS NDVI and previous years' temperature and precipitation. Note that extreme temperature in previous year causes NDVI to drop. The straight line is fitted using ordinary least square method, while the zigzagging curve is fitted using robust regression, assuming a multivariate t distribution, which is less affected by outliers.



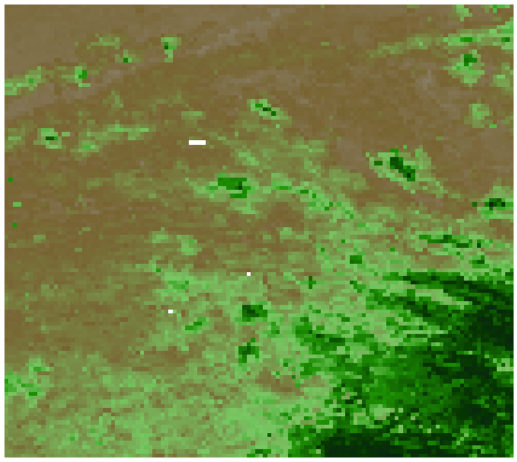
(b) August

Figure 5.3: Scatter plot matrix of average GIMMS NDVI and previous years' temperature and precipitation. Higher temperature or precipitation in previous year has no significant influence on NDVI. The straight line is fitted using ordinary least square method, while the zigzagging curve is fitted using robust regression, assuming a multivariate t distribution, which is less affected by outliers.

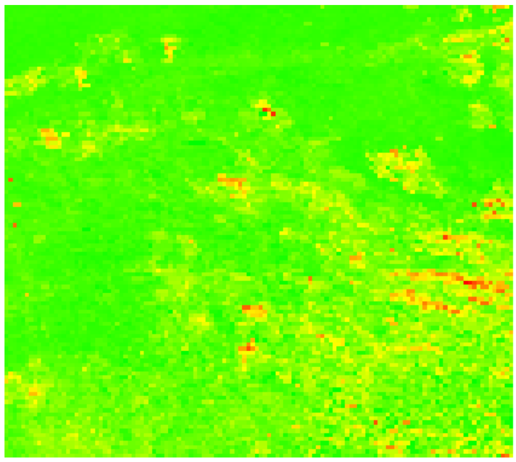


(c) September

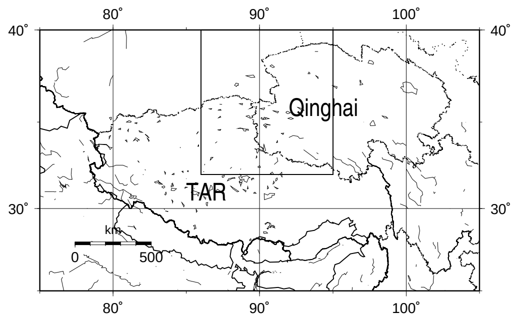
Figure 5.3: Scatter plot matrix of average GIMMS NDVI and previous years' temperature and precipitation. The straight line is fitted using ordinary least square method, while the zigzagging curve is fitted using robust regression, assuming a multivariate t distribution, which is less affected by outliers. Note that higher temperature at this period enhances NDVI.



(a)



(b)



(c)

Figure 5.4: (a) Maximum possible NDVI value derived from the 23-year AVHRR GIMMS data and (b) difference between maximum possible NDVI and actual NDVI values in El Niño year 1985, the yellow and red pixels denotes high difference and low actual NDVI values. The box in (c) shows the coverage of the images.

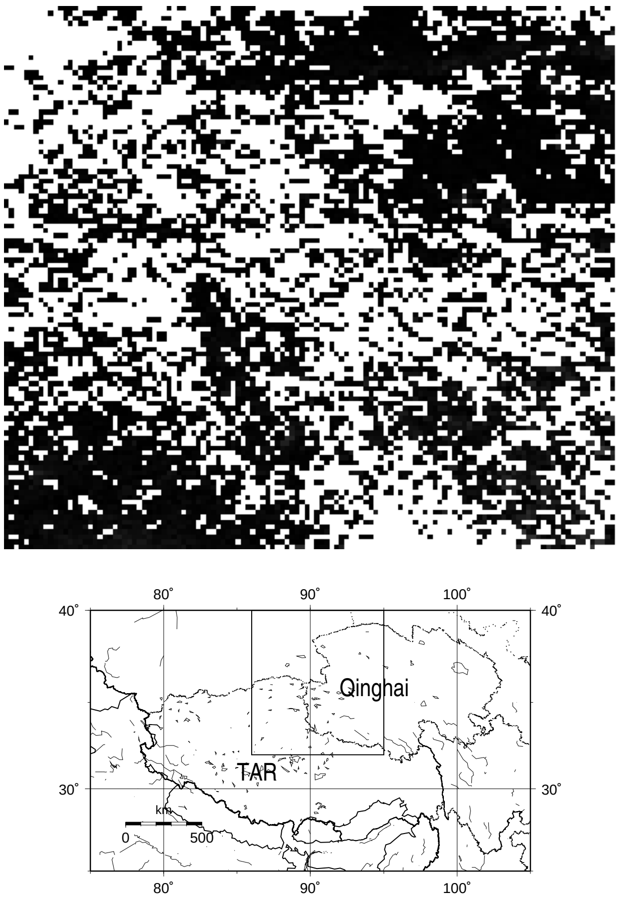
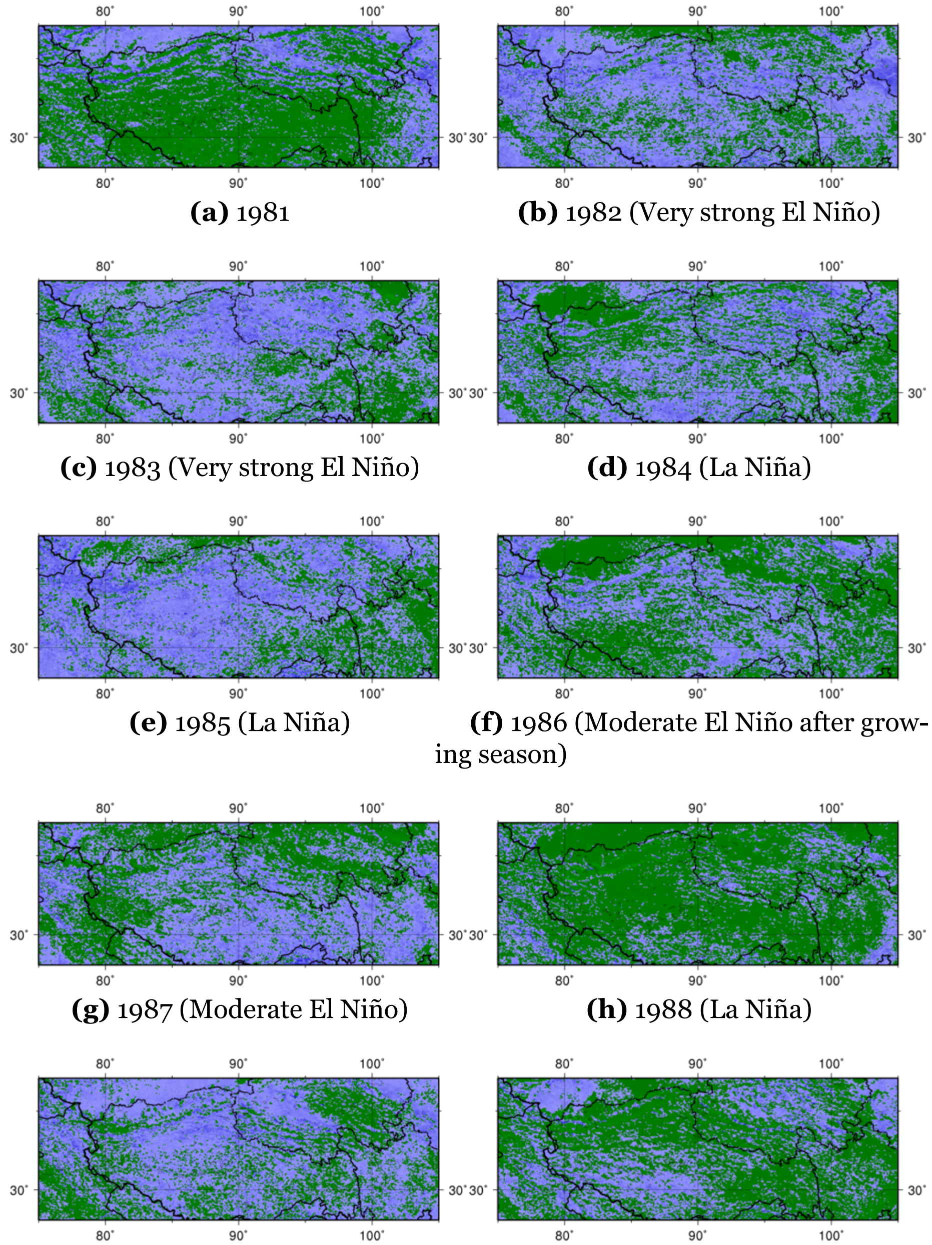


Figure 5.5: The result of subtracting NDVI values of 1986 (non-El Niño year) from those of 1985 (El Niño year). White pixels stand for reduction of NDVI from 1985 to 1986 (negative values) while black pixels denotes increase of NDVI.



(a) 1981

(b) 1982 (Very strong El Niño)

(c) 1983 (Very strong El Niño)

(d) 1984 (La Niña)

(e) 1985 (La Niña)

(f) 1986 (Moderate El Niño after growing season)

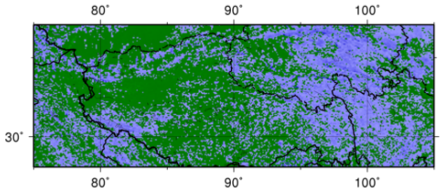
(g) 1987 (Moderate El Niño)

(h) 1988 (La Niña)

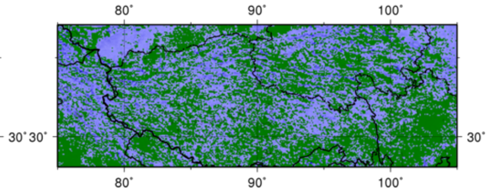
(i) 1989

(j) 1990

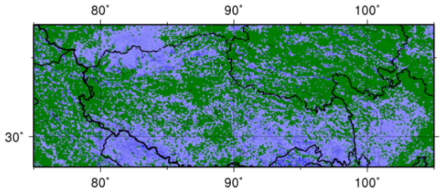
Figure 5.6: Growing season NDVI anomaly map for period 1981 – 2003 on the Tibetan Plateau, green stands for positive anomaly while blue stands for negative anomaly. The information on El Niño and La Niña occurrences is from Quinn et al. (1987), Cane (2005), Hong et al. (2001).



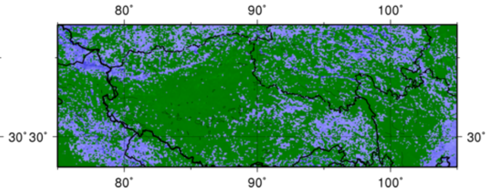
(k) 1991 (Prolonged El Niño)



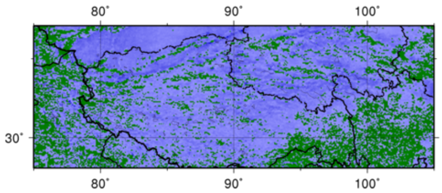
(l) 1992 (Prolonged El Niño)



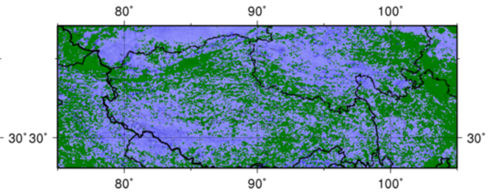
(m) 1993 (Prolonged El Niño)



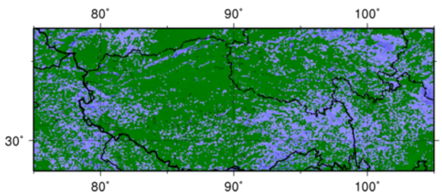
(n) 1994



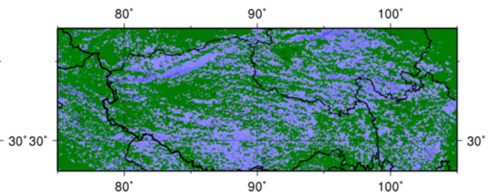
(o) 1995 (La Niña after growing season)



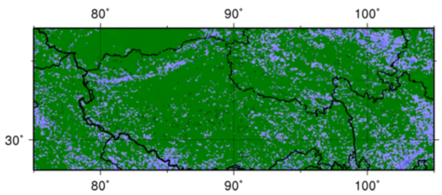
(p) 1996



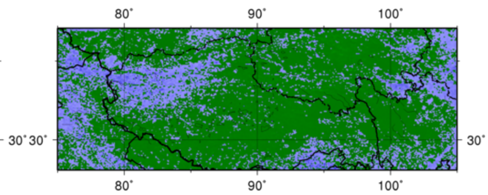
(q) 1997 (Strong El Niño)



(r) 1998 (Strong El Niño)

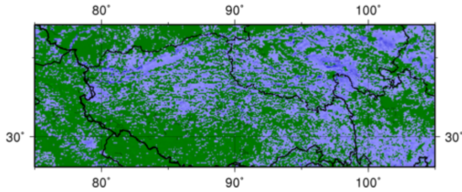


(s) 1999

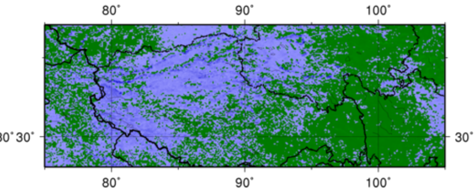


(t) 2000

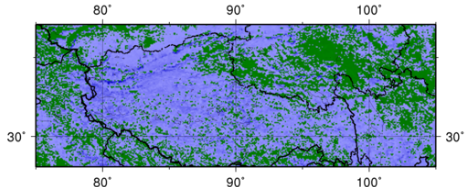
Figure 5.6: Growing season NDVI anomaly map for period 1981 – 2003 on the Tibetan Plateau, green stands for positive anomaly while blue stands for negative anomaly. The information on El Niño and La Niña occurrences is from Quinn et al. (1987), Cane (2005), Hong et al. (2001).



(u) 2001 (Moderate El Niño)



(v) 2002 (Moderate El Niño)



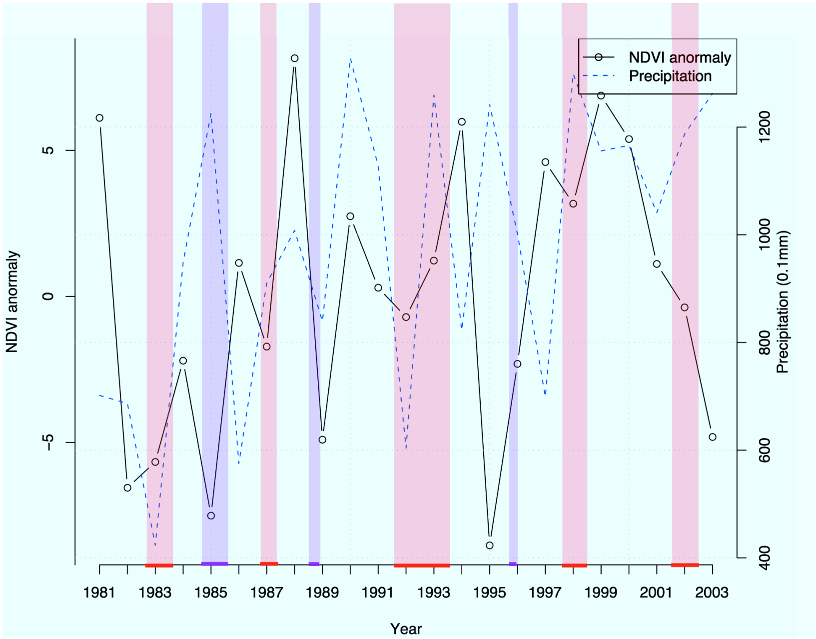
(w) 2003

Figure 5.6: Growing season NDVI anomaly map for period 1981 – 2003 on the Tibetan Plateau, green stands for positive anomaly while blue stands for negative anomaly. The information on El Niño and La Niña occurrences is from Quinn et al. (1987), Cane (2005), Hong et al. (2001).

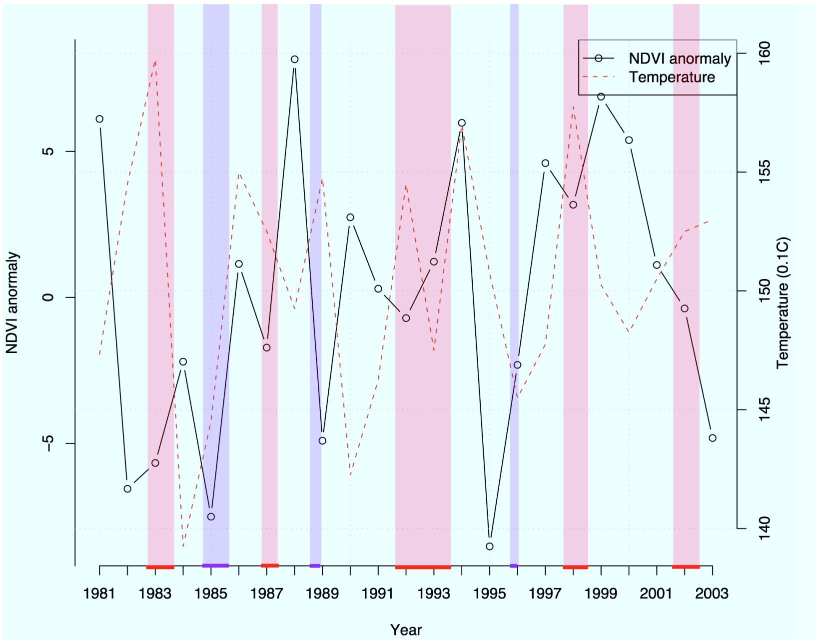
ure 5.8), the mean anomaly for these three years are 8.48, -12.80, and 10.19.

The distribution of NPP data was analysed by drawing box and whisker plots for each month. Four of the box plots, illustrating NPP anomalies in March, June, September and December for the years 1982 to 2003, are shown in Figure 5.9. The four months represent vegetation after the winter grazing, at the beginning and end of growing season, and start of winter grazing, respectively. It is worthy noting that number of valid pixels in December and January images was much less than in other images due to unavailability of precipitation and temperature data in these months, thus conclusions on other months cannot be drawn directly from them. It is apparent that the mean values of NPP anomaly do not change greatly from year to year. But changes in smaller areas may be more manifested, as the December images show.

Moreover, a visual comparison of NPP anomaly images (not shown here) also shows that in some years NPP decreases take place mainly on open shrub land cover type, while the overall average may change only a



(a) NDVI anomaly and precipitation



(b) NDVI anomaly and temperature

Figure 5.7: NDVI anomaly from 1981 to 2003, overlaid with growing season precipitation and temperature in the same period. Red boxes indicate El Niño periods; purple boxes indicate La Niña periods.

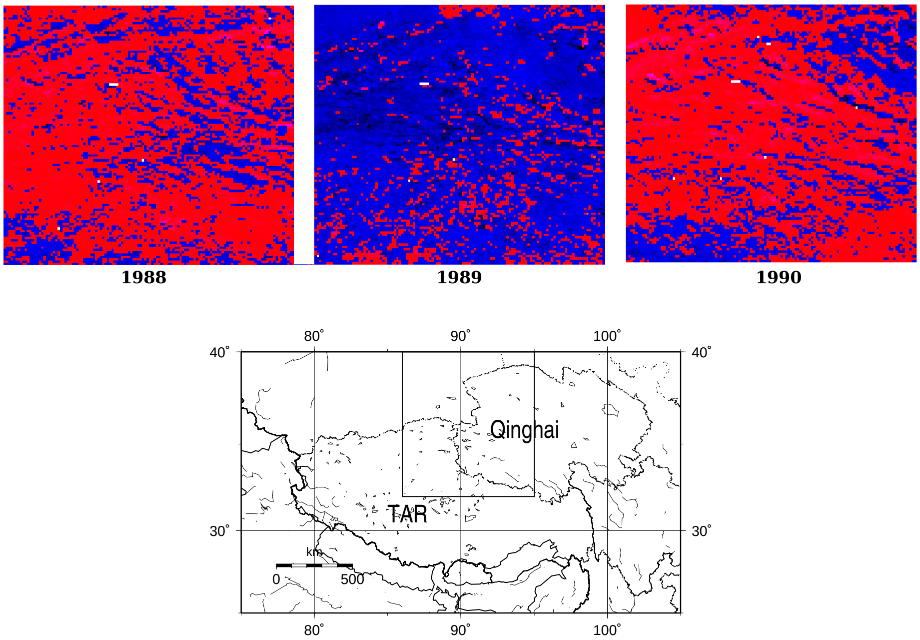
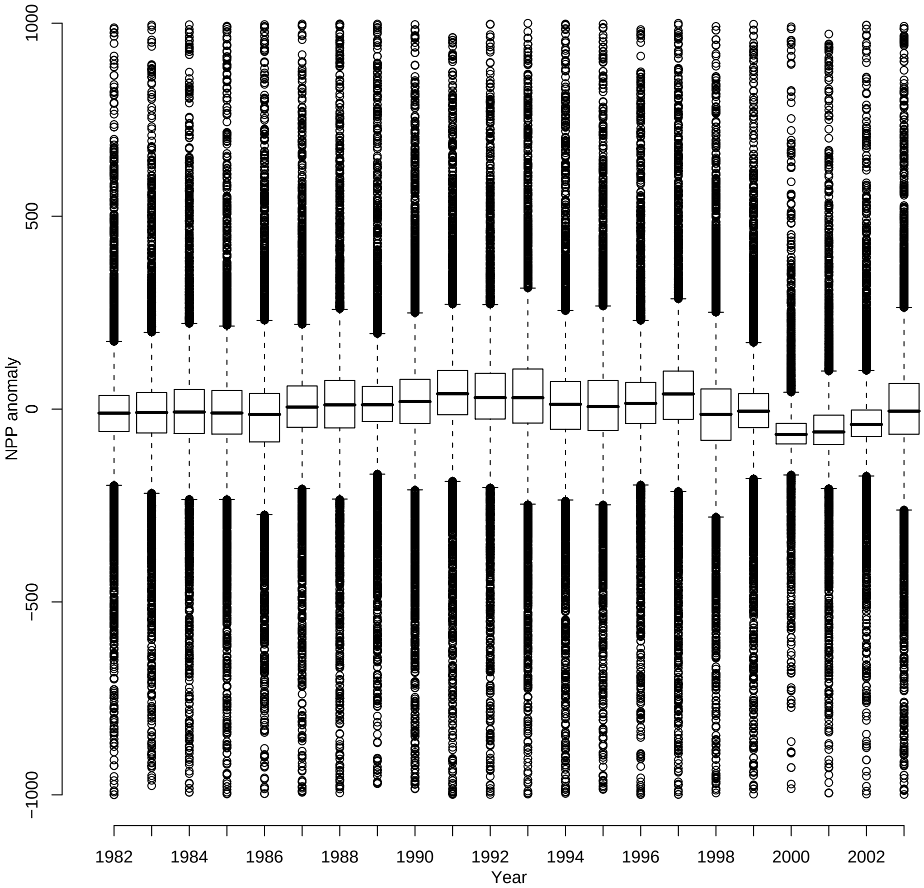


Figure 5.8: NDVI anomaly of Northern Tibet in 1988 (left), 1989 (middle) and 1990 (right). Red pixels denote NDVI higher than average and blue pixels denote NDVI lower than average.

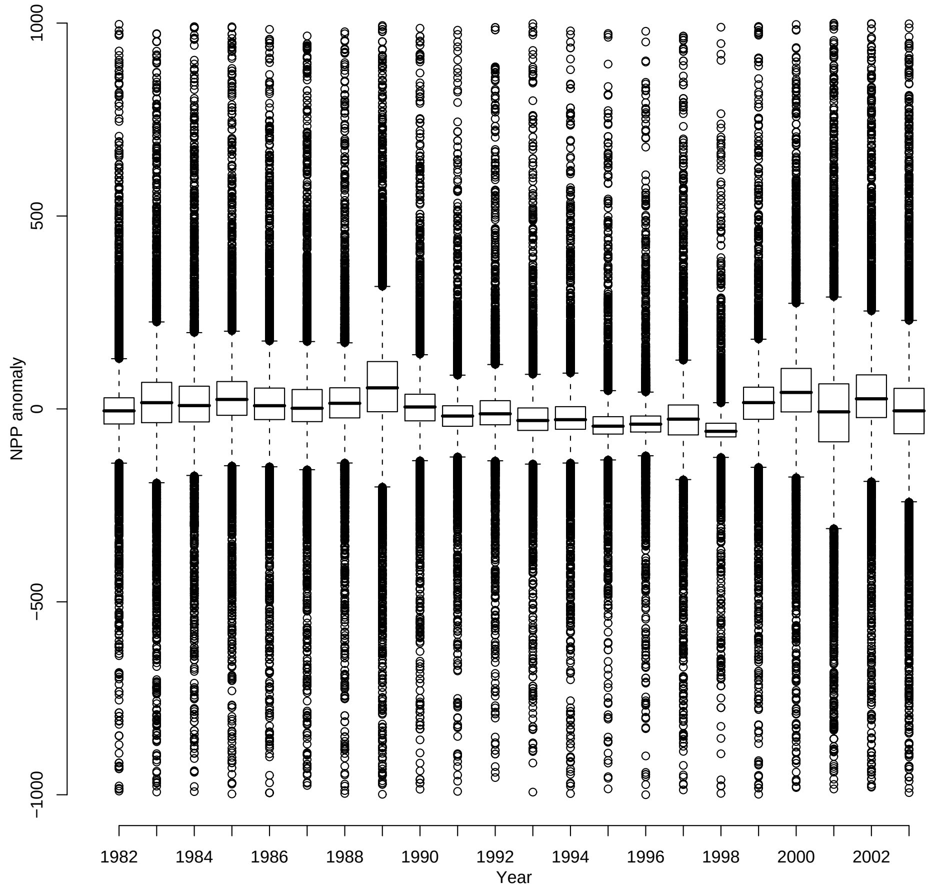
little. The NPP anomaly image shows that in the early 1990s there was a disturbance in NPP values, featuring large area of reduced NPP in summer and relatively larger NPP in winter, which lasted a few years. The impact was generally constrained to the centre of the northern Tibetan Plateau, while the northwestern and southeastern corner are less affected. Compared with the landcover map, it can be deduced that grasslands are more likely to be influenced in such disturbance. Similar phenomena took place in 1984, 1985, 1989, 1990, 1991, 1992, 1994, 1995, and 1997. In these years ENSO activities of different intensity are recorded, therefore it is possible that ENSO caused a decrease of NPP. By examining temperature distribution in these years and in years when NPP are not negatively impacted, it is found that temperature on grasslands in these low NPP years are generally higher (Figure 5.10). Probably as a result, the estimated evapotranspirations were also higher. The following winter's NPP was also reduced. However, for shrubland and woodland, the changes were mixed.

The other areas were similarly analysed. It was found that ENSO has



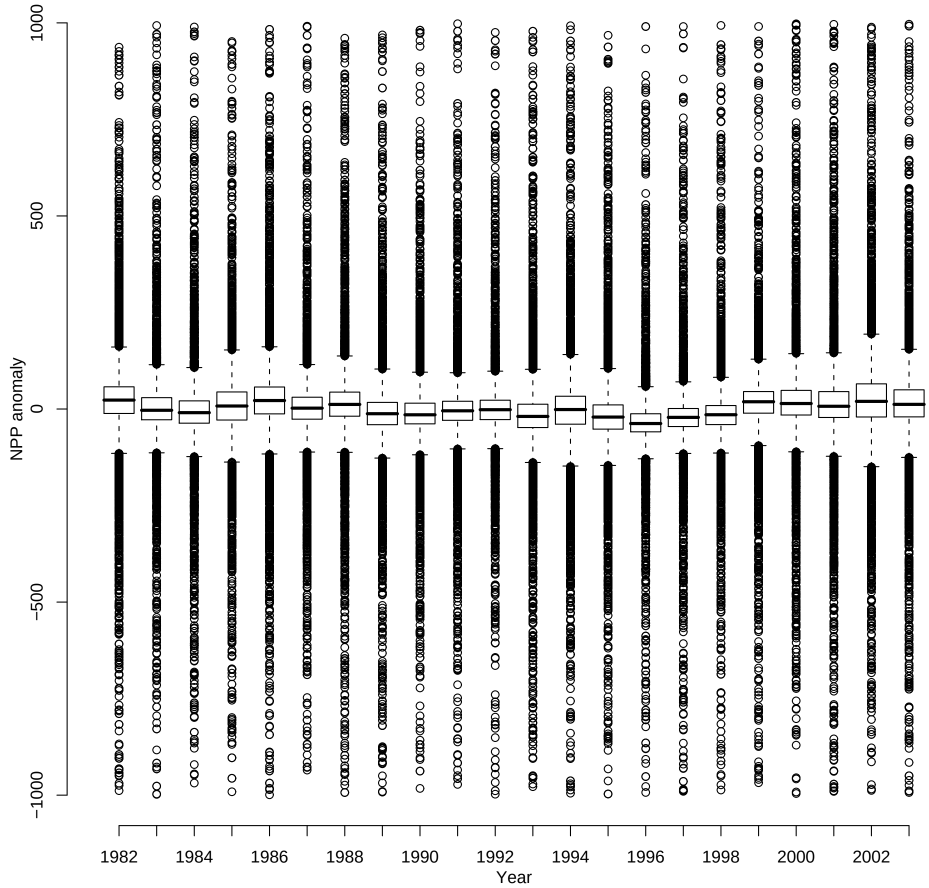
(a) March

Figure 5.9: NPP anomaly box plot of 4 months for a period of 22 years, drawn using the anomaly data calculated for each pixel on the map. Black dots are outliers. The average values of NPP do not change significantly in different years.



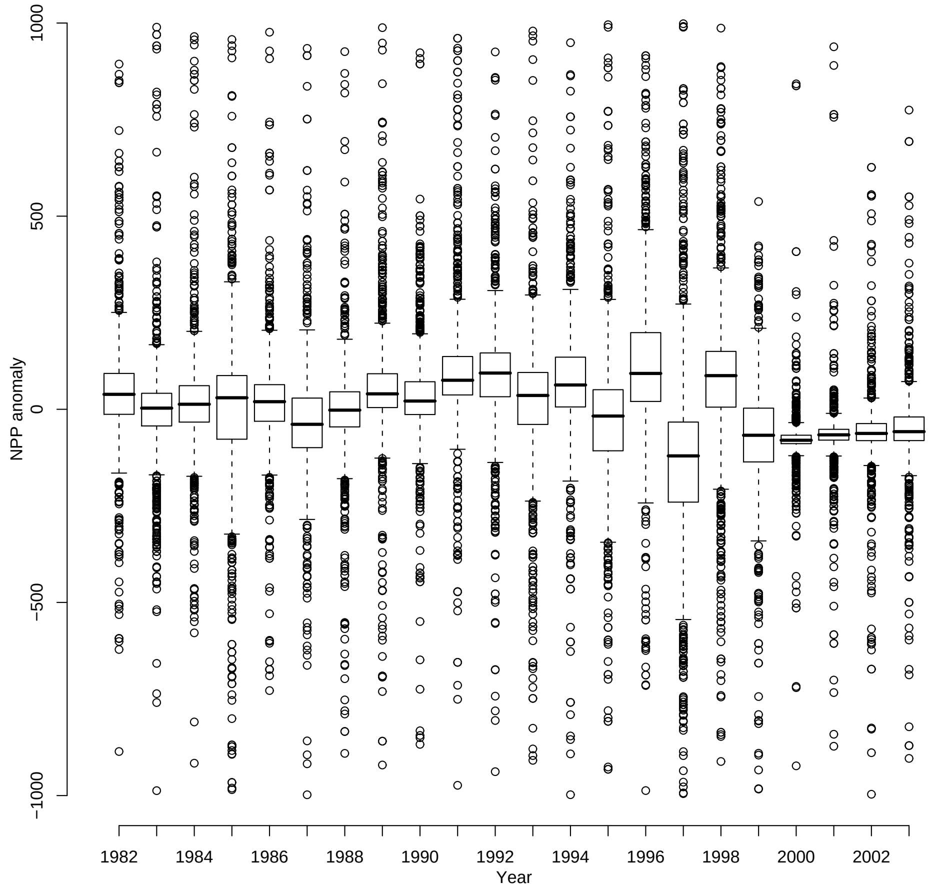
(b) June

Figure 5.9: NPP anomaly box plot of 4 months for a period of 22 years, drawn using the anomaly data calculated for each pixel on the map. Black dots are outliers. The average values of NPP do not change significantly in different years.



(c) September

Figure 5.9: NPP anomaly box plot of 4 months for a period of 22 years, drawn using the anomaly data calculated for each pixel on the map. Black dots are outliers. The average values of NPP do not change significantly in different years.



(d) December

Figure 5.9: NPP anomaly box plot of 4 months for a period of 22 years, drawn using the anomaly data calculated for each pixel on the map. Black dots are outliers. The average values of NPP do not change significantly in different years.

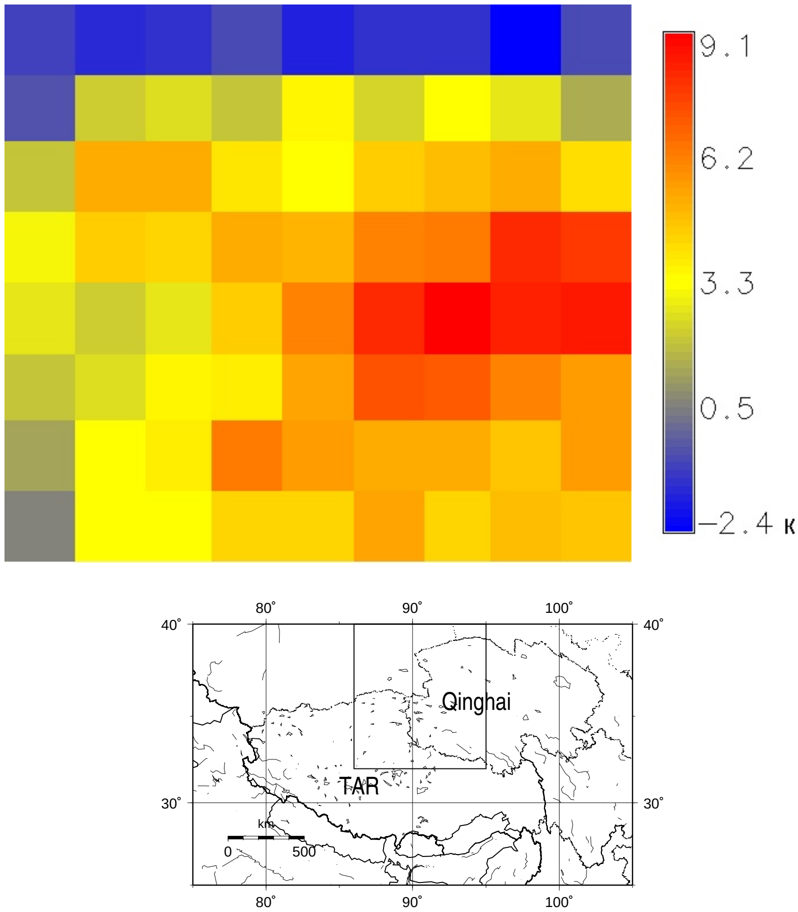


Figure 5.10: Temperature difference map at 1°resolution, showing temperature difference by subtracting temperature of August 2001, from that of August 1991, an ENSO year

more significant negative impact on grassland and "bare ground" and little or positive impact on woodland. The NPP anomaly in these areas exhibits similar patterns to that in the northern Tibetan Plateau, with no significant difference between different years.

5.3 Trends and disturbance

5.3.1 Detrended fluctuation analysis

The result of the DFA conducted on the monthly NDVI Northern Tibet area average is shown in Figure 5.11. A linear model fitting using all points in the time series shows that $\alpha = 0.9547 \pm 0.0187$, indicating a possible 1/f noise fluctuation. However, a fitting using the first half of the $F(n)$-n pairs denoting smaller box size and time scale shows $\alpha = 1.110 \pm 0.053$, indicating random walk behaviour of the time series at small time interval (see Table 4.2). Fitting the rest of the pairs gives $\alpha = 0.921 \pm 0.056$, implying that the behaviour of NDVI readings at large time scale is more close to a power-law correlation. Such cross-over of α is the result of the combination of multiple influences on NDVI data. In order to work out at which time scale the cross-over takes place, fitting is conducted using different subsets. It was found that at the time scale of about 28 months α becomes significantly less than 1.

Telesca et al. (2006) in a study of Italian forest ecosystem shows a similar result, indicating the presence of long-range correlation. The implication is that if a positive feedback exists, a perturbation will cause a larger one in the long-term future. However, such correlations only exist at large time scales, suggesting that the disturbance trend is only visible in the long term. In the short term such as within a year or a season, the fluctuation is dominated by random-walk like behaviour. Considering such characteristics in the grassland setting, it can be summarised that each

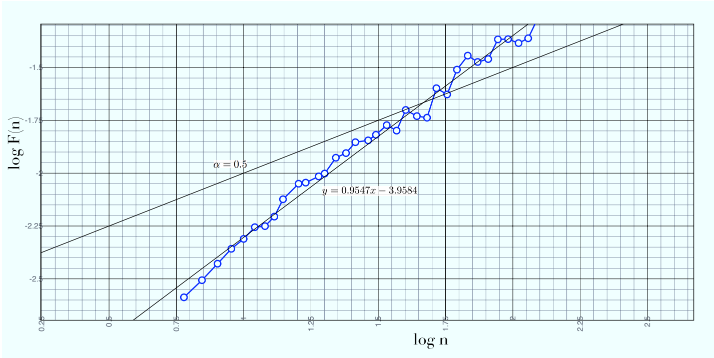


Figure 5.11: Result of DFA2 on NDVI area average data. The $\log F(n)$-$\log n$ pairs shows certain collinearity. The $\alpha = 0.5$ line was also drawn as a reference. The long-range end's α is less than 1 but larger than 0.5, suggesting a positive correlation between fluctuations.

time a disturbance event takes place, it may be correlated to future disturbances that take place over 28 months or longer. The positive correlation means the impact of disturbances becomes greater in the subsequent occurrences, possibly due to the impact of previous ones. However, the causal link cannot be established yet.

The same process conducted on Southern, Eastern and Western Tibet's NDVI data yields similar results, all indicating a positive correlation with $0.5 < \alpha < 1$. Compared to Northern Tibet, the α values are smaller, suggesting a more obvious correlation. However, the pixel-by-pixel results derived from DFA on individual pixels in four subareas show that for most pixels $\alpha < 0$, indicating an anti-correlation.

5.3.2 Persistence of NPP trends

The value of each pixel on the persistence map indicates for how long a positive or negative trend has persisted on the pixel. For Northern Tibet, the persistence trend on the 22-year map is not obvious. The largest time of survival for a positive trend is 11 years while that for a negative trend is 18 years, but pixels at either extremes are rare. 86.5% of pixels have values between +5 and -5, shows that no long-term trend can be found for

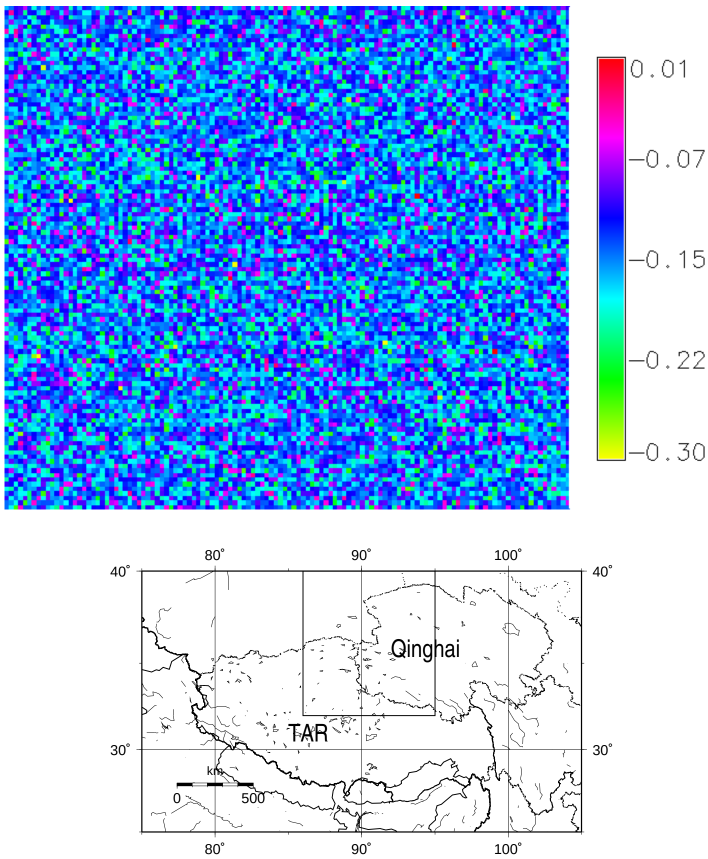


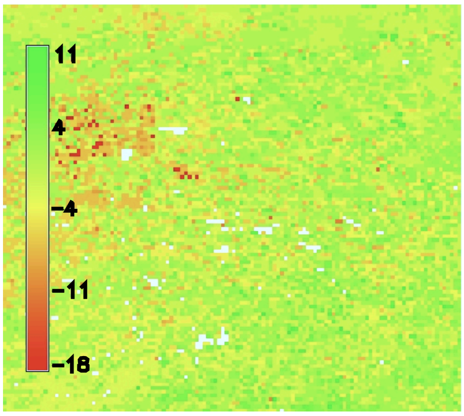
Figure 5.12: Pixel-by-pixel result of DFA2 on Northern Tibet. Most pixels have $\alpha < 0$, indicating possible anti-correlation between disturbance and time.

these pixels in the 22 years. However, a comparison with the two 10-year map reveals that the 1982 – 1991 data's positive trend has a larger contribution to the trend on the 22-year data, while the 1992 – 2001 data has obvious negative persistent trend, especially in the east of the map where a centre of heat resided in the mid-1990s (Figure 5.13). The diminished trend on the 22-year map may be the result of cancelling of trends in the calculation.

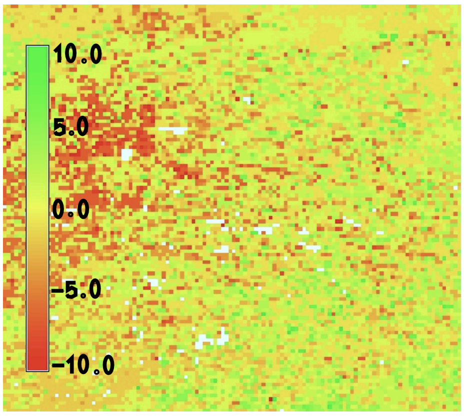
A examination of 5-year maps (not shown here) found that on the plateau NPP negative anomalies tended to have longer life span, i.e. persist in position for a longer period. The positive anomalies appear in a fragmented manner, may persist in some isolated locations for relatively long time but not as long as negative anomalies. Both negative pixels on the 1982 – 1986 map and the 1992 – 1996 map persisted through the next map, although somewhat alleviated by later years' positive values. The negative values on the 1997 – 2001 map occupy larger area than on the 1992 – 1996 map, indicating a possible spatial expansion of the negative trend. The survival time of the negative trend is also apparently longer than the 1982 – 1986 one.

The interpretation of El Niño periods' map has difficulties as the exact years when El Niño's effect began to appear and disappear cannot be determined. However, these maps suggest the El Niño tend to have impacts on the east side of the map, and the negative trend is more persistent on the north slopes. The comparison of the 1984, 1991 and 1997 maps shows that the impact area of later El Niño is also larger than the earlier ones (Figure 5.14).

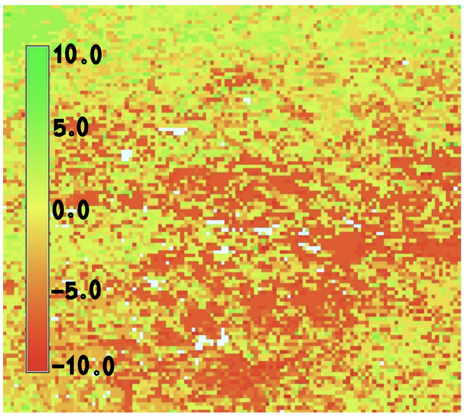
For Southern Tibet the impact of El Niño is more significant in the eastern part of the map. From 1980s to 1990s the negative trend shifted from the west to the east. The life span of negative trend after El Niño is shorter than that in Northern Tibet. In Western Tibet the pattern of



(a) NPP trend persistence for 1982 – 2003

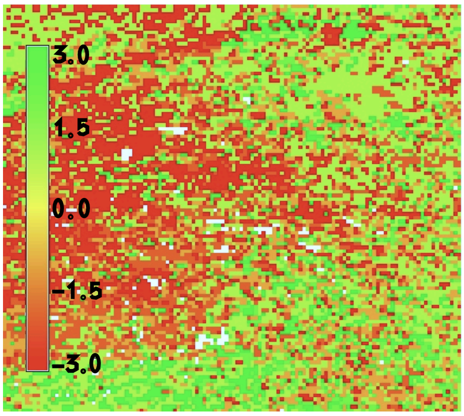


(b) NPP trend persistence for 1982 – 1991

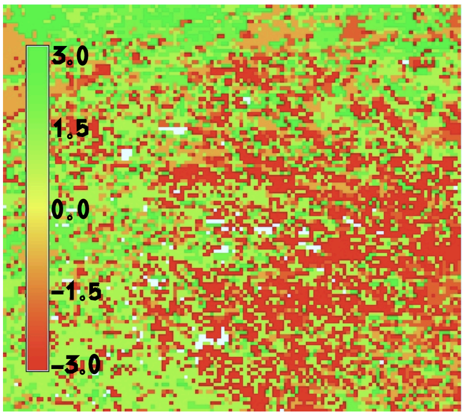


(c) NPP trend persistence for 1992 – 2001

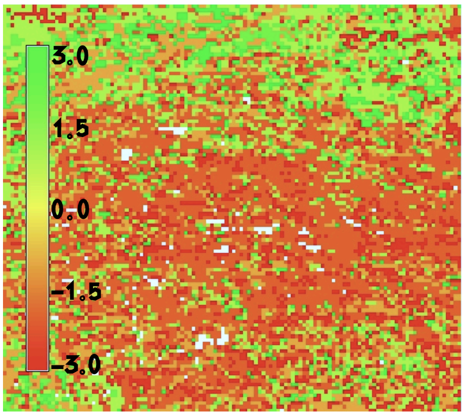
Figure 5.13: NPP trend persistence maps for the periods 1982 – 2003, 1982 – 1991 and 1992 – 2001 in Northern Tibet. The positive value is the number of consecutive years when NPP has positive anomalies while the negative value stands for the number of consecutive years when NPP has negative anomalies. Note the difference between two 10-year maps.



(a) NPP trend persistence for 1984 – 1986



(b) NPP trend persistence for 1991 – 1993



(c) NPP trend persistence for 1997 – 1999

Figure 5.14: NPP trend persistence map for three El Niño periods around 1984, 1991 and 1997. Note that the area of El Niño impact in 1997 is larger than in 1991 which is larger than in 1984.

negative persistence is limited to certain areas in the northwestern corner of the plateau, but these negative pixels have a very long survival time. In the Eastern Tibet the negative trend is quick to reverse. However, places with negative NPP anomalies before also tend to have a negative trend afterwards.

5.4 Spatial patterns

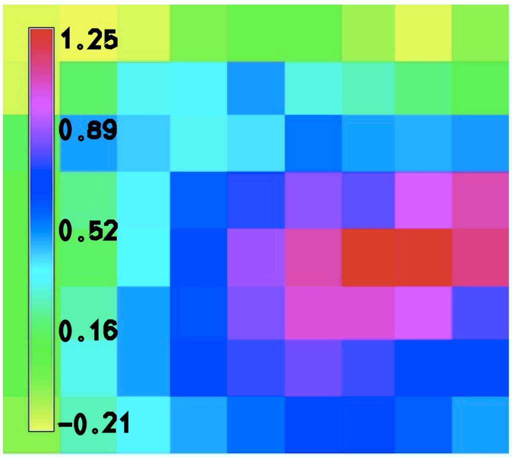
Spatial factors such as topography have effects on the response of the vegetation index in the face of changes. In areas with a relatively low altitude (< 3000 m), higher temperature is linked with higher NDVI values (positive anomalies), but in high altitude areas the relationship is reversed: higher temperature leads to negative NDVI anomalies (see Figure 5.15). This is especially evident on the images recording data from 1991 to 1999, when a centre of increased temperature resided over the northern Tibetan Plateau.

Topography also causes different vegetation conditions in an area. Negative NDVI anomalies tend to appear more on north slopes, even when adjacent south slopes shows positive anomalies (Fig. 5.16). This is most obvious in El Niño years.

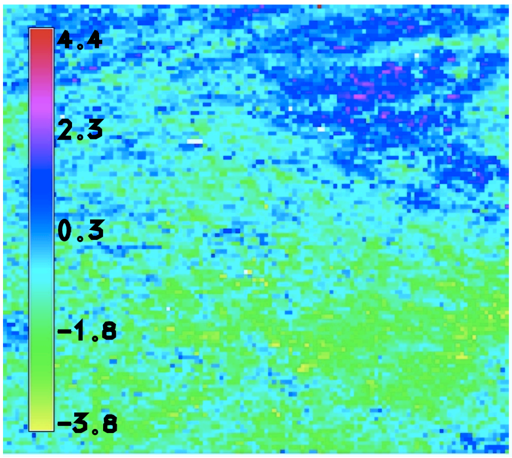
By calculating the standard deviation of 22 years' summer NDVI for each pixel and comparing with landcover data it is found that grassland tend to have higher variations in different years, while shrubland and bare ground have lower variations.

5.5 Model simulation

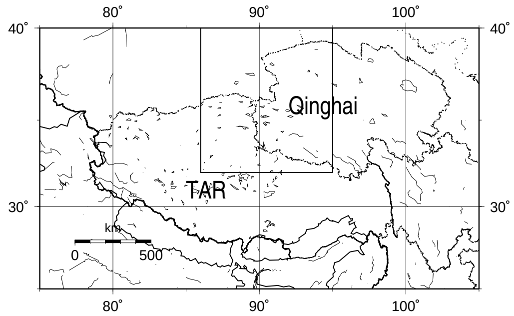
With information provided by analyses described in previous sections, the pattern of disturbance and response was revealed. But knowing the behaviour of the system in its current condition is not enough. Resil-



(a)

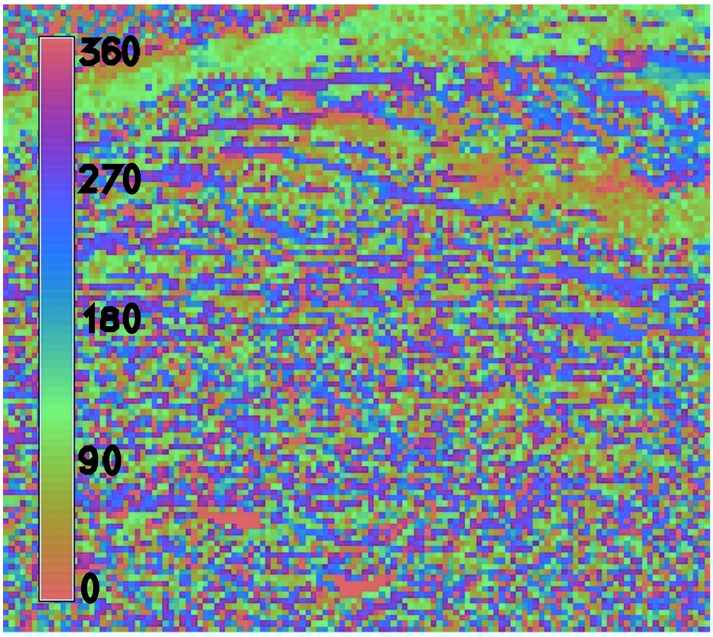


(b)

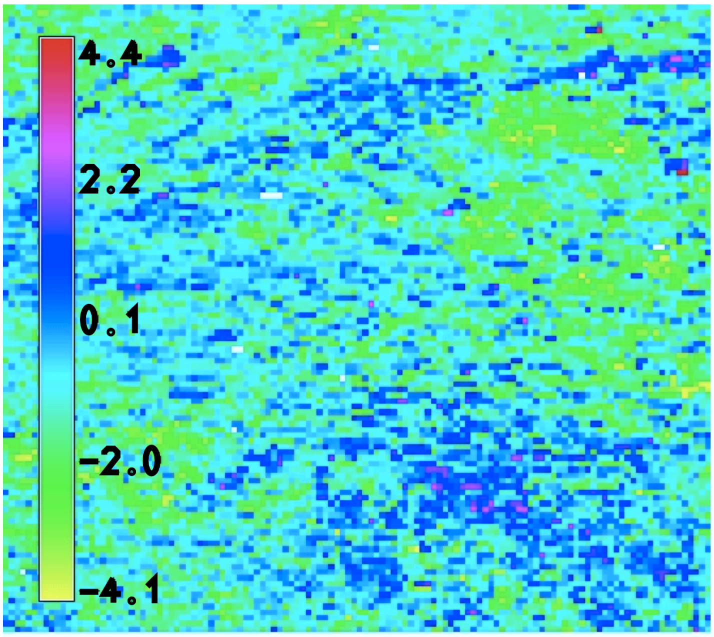


(c)

Figure 5.15: Figure (a) shows the area of increased temperature in Northern Tibet in July 1995. Figure (b) shows the NDVI values presented as z-score in the same month. Figure (c) shows the geographical coverage of the images.



(a)



(b)

Figure 5.16: The aspect image (a) and NDVI z-score (difference from mean value measured by standard deviation) image of July 1984 (b). Note the aspect pattern reflected in the z-score pattern, with most negative z-scores occuring on north slopes.

ience assessment requires understanding the response of the system under changed disturbance conditions. More detailed research was limited by the availability of data, but the results described below can at least provide qualitative information about various disturbance scenarios.

5.5.1 Null model

In a null model, the goal is that the ratio of grass and shrub should remain constant apart from some fluctuations throughout time. Neither should either shrub or grass diminish in abundance. A set of parameters satisfying these conditions are listed below:

```
g:grass_quantity 1
w:shrub_quantity 1
r_{g}:growth_rate_grass 0.09
r_{w}:growth_rate_shrub 0.11
s:grazing_intensity 0.38
c_{wg}:competition 0.16
c_{gw}:competition 0.16
c_{gg}:competition 0.3
c_{ww}:competition 0.3
e_{g,w}:disturbance 0.1
e_{l}:livestockdisturbance 0.1
c_{e}:recovery_rate 0.5
cl_{e}:livestockrecovery_rate 0.75
c_{f}:fire_risk 0
years 150
distprobab 0.3
```

The trajectory of the system is shown in Figure 5.17. At the end of simulation the abundances of shrub and grass have maintained a ratio close to

1:1. It was found that the final abundances of grass and shrub depend on the intraspecies competition coefficient c_{gg} and c_{ww}, while the increase of interspecies competition coefficient led to the hysterical behaviour appearing early in the simulation, and the impact of disturbance was more pronounced. The change of growth rate has limited influence on the final ratio of shrub to grass, as long as shrub growth rate is higher than that of grass. The initial abundances of shrub and grass do not greatly influence the final ratio either, due to negative feedback caused by intraspecies competition.

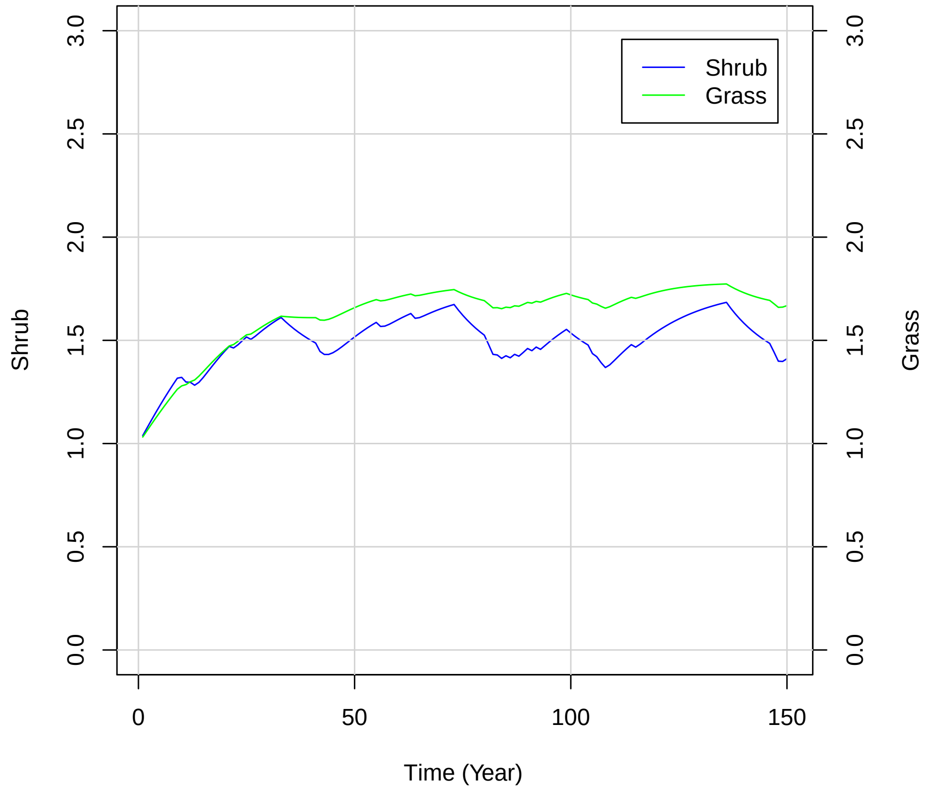


Figure 5.17: Trajectory of the shrub/grass system in the null model projected to 150 years in the future. The other simulation results are of the same time period unless specified otherwise. Small disturbance can cause significant trends of change lasting many years.

5.5.2 Scenarios

The simulation result of a standard scenario with light grazing, moderate and infrequent disturbance that rapidly recover is shown in Figure 5.18.

The figure shows that in the competition between grass and shrub, given the same initial abundance, both grass and shrub increase at a similar pace. When a pair of equilibrium values is reached, the system undulates around the equilibrium point. The pattern has no significant changes in different runs of the model. By changing the initial grass/shrub abundance, it is clear that the system returns to the same point of equilibrium (Figure 5.19). In longer simulations the grass and shrub abundance have only small changes around the equilibrium. The parameter settings for the two runs are listed below:

```
g:grass_quantity 1
w:shrub_quantity 1
r_{g}:growth_rate_grass 0.09
r_{w}:growth_rate_shrub 0.11
s:grazing_intensity 0.1
c_{wg}:competition 0.16
c_{gw}:competition 0.16
c_{gg}:competition 0.3
c_{ww}:competition 0.3
e_{g,w}:disturbance 0.1
e_{l}:livestockdisturbance 0.1
c_{e}:recovery_rate 1
cl_{e}:livestockrecovery_rate 1.2
c_{f}:fire_risk 0
years 150
distprobab 0.3
```

```
g:grass_quantity 1
w:shrub_quantity 2.5
r_{g}:growth_rate_grass 0.09
```

```
r_{w}:growth_rate_shrub 0.11

s:grazing_intensity 0.1

c_{wg}:competition 0.16

c_{gw}:competition 0.16

c_{gg}:competition 0.3

c_{ww}:competition 0.3

e_{g,w}:disturbance 0.1

e_{l}:livestockdisturbance 0.1

c_{e}:recovery_rate 1

cl_{e}:livestockrecovery_rate 1.2

c_{f}:fire_risk 0

years 150

distprobab 0.3
```

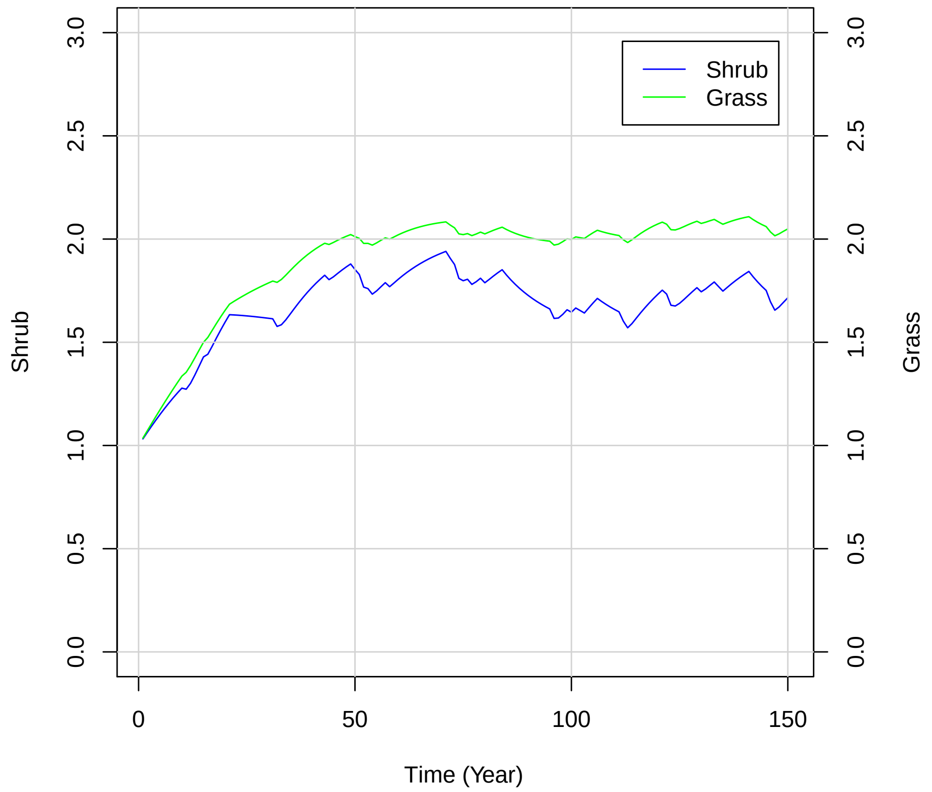


Figure 5.18: A standard scenario with light grazing. The fluctuation is more frequent for both grass and shrub abundances.

The second scenario illustrates the outcome of a climate change-induced drop of recovery rate from disturbances and higher disturbance probabil-

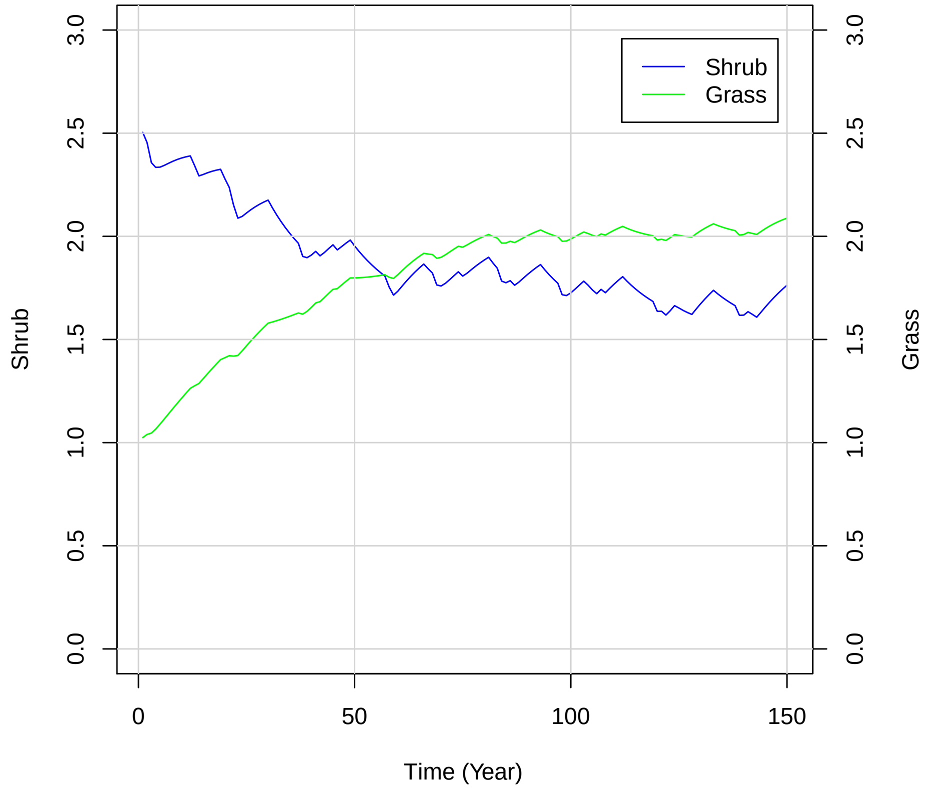


Figure 5.19: Grass and shrub abundance after entering the hysteric domain. Changed initial abundance yields the same point of equilibrium.

ity and fire risk. It can be seen that although shrubs have a higher growth rate, eventually their abundance is smaller than grass at the equilibrium point. At first shrub and grass abundance increases rapidly despite some fluctuations due to disturbance and then both types of vegetation enters a hysteric dynamic pattern (Figure 5.20). It is noted that the pattern changes slightly between each run, although the general trend does not change. From the long-term simulation results it can be seen that in the long run grass abundance will fluctuate around a constant value, while shrub abundance will fluctuate more significantly at two time scales, as Figure 5.21 shows. The parameters for this scenario are listed below:

```
g:grass_quantity 1

w:shrub_quantity 1

r_{g}:growth_rate_grass 0.09

r_{w}:growth_rate_shrub 0.11
```

```
s:grazing_intensity 0.38

c_{wg}:competition 0.16

c_{gw}:competition 0.16

c_{gg}:competition 0.3

c_{ww}:competition 0.3

e_{g,w}:disturbance 0.1

e_{l}:livestockdisturbance 0.1

c_{e}:recovery_rate 0.75

cl_{e}:livestockrecovery_rate 1.2

c_{f}:fire_risk 0.01

years 150

distprobab 0.4


g:grass_quantity 1

w:shrub_quantity 1

r_{g}:growth_rate_grass 0.09

r_{w}:growth_rate_shrub 0.11

s:grazing_intensity 0.38

c_{wg}:competition 0.16

c_{gw}:competition 0.16

c_{gg}:competition 0.3

c_{ww}:competition 0.3

e_{g,w}:disturbance 0.1

e_{l}:livestockdisturbance 0.1

c_{e}:recovery_rate 0.75

cl_{e}:livestockrecovery_rate 1.2

c_{f}:fire_risk 0.01

years 1500

distprobab 0.4
```

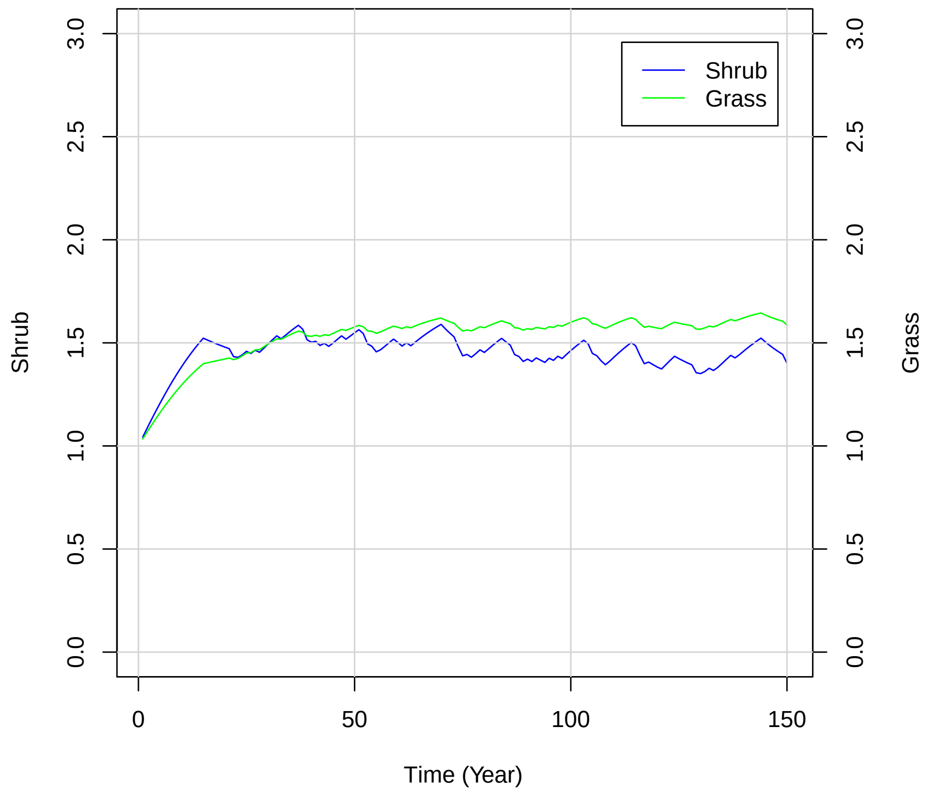


Figure 5.20: Grass and shrub abundance with more frequent disturbance and lower recovery rate in climate change conditions. The equilibrium is established at a lower level of vegetation abundances, especially for grass. The fluctuation of shrub is more pronounced.

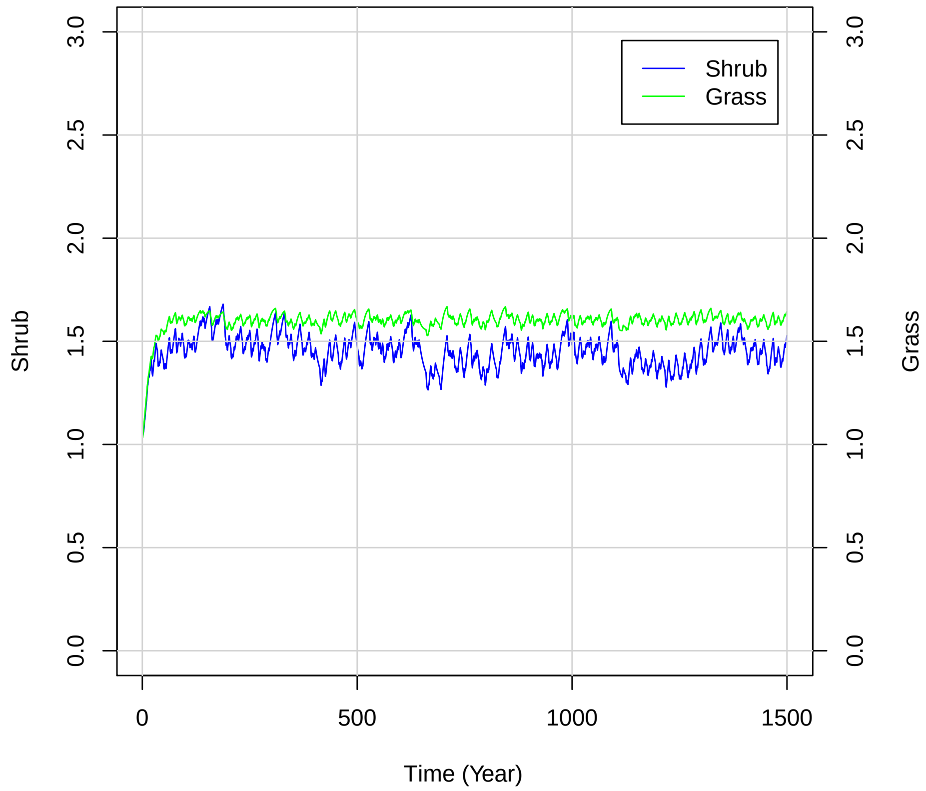


Figure 5.21: Grass and shrub abundances with more frequent disturbance and lower recovery rate in climate change conditions with longer simulation period (1,500 years), showing that in the long term the impact of climate change puts the vegetation abundances in a domain of attraction of lower level. The fluctuation of shrub is more significant and lasts longer.

The third scenario simulates urbanisation, which leads to less grazing intensity as well as availability of grass. The simulation result is shown in Figure 5.22. In this scenario, both shrub and grass abundance increase near the initial level, until shrub abundance reaches a maximum level. The shrub abundance decreases slightly afterwards, while the grass abundance continues to increase but with changes in the pace of increase. In a long-term simulation, grass abundance will continue to increase at the cost of shrub abundance. The parameter set for this scenario is as follows:

```
g:grass_quantity 0.5
w:shrub_quantity 1
r_{g}:growth_rate_grass 0.09
r_{w}:growth_rate_shrub 0.11
s:grazing_intensity 0.30
c_{wg}:competition 0.16
c_{gw}:competition 0.16
c_{gg}:competition 0.3
c_{ww}:competition 0.3
e_{g,w}:disturbance 0.1
e_{l}:livestockdisturbance 0.1
c_{e}:recovery_rate 1
cl_{e}:livestockrecovery_rate 1.2
c_{f}:fire_risk 0
years 150
distprobab 0.3
```

In the transition scenario, the system changes from nomadic pastoralism to ranch-like practices, as a result, the recovery rate is reduced from 1 to 0.66, the livestock recovery rate reduced from 1.2 to 1, and the disturbance probability decrease from 0.3 to 0.2, to simulate the behaviour of ranches with fewer disturbance events but slower to recover from one.

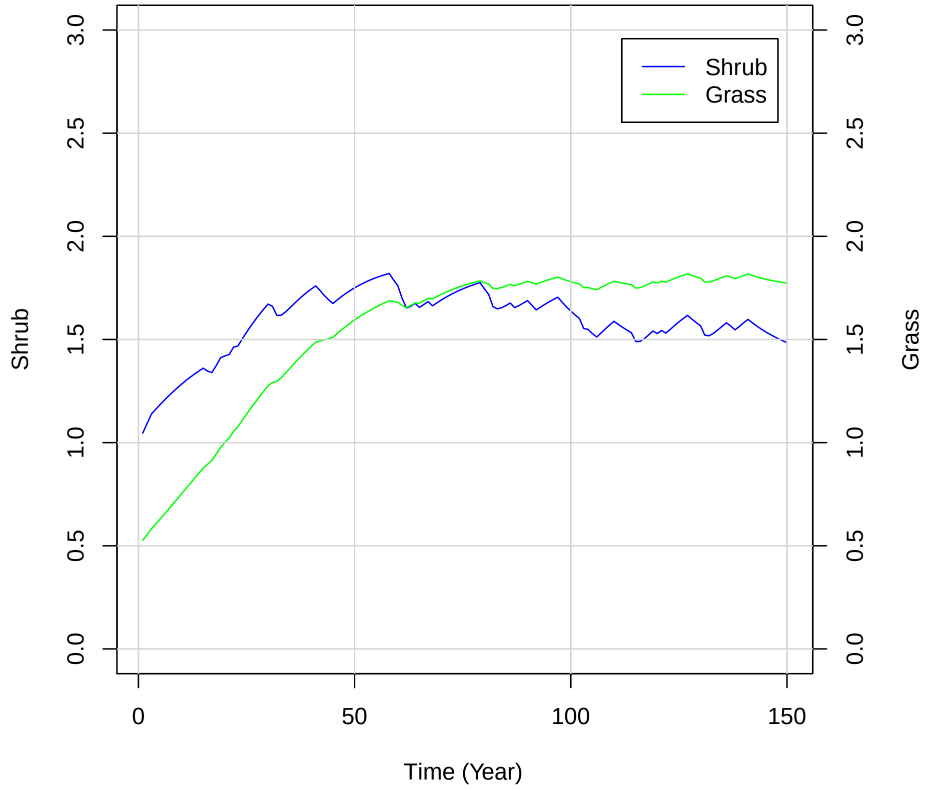


Figure 5.22: Grass and shrub abundance with less pastures and grazing. Grass in reduced grazing condition has advantage over shrub when the system reaches the domain of attraction.

In the first 20 years the pastoralists are nomadic, and in the following 130 sedentary. In this scenario, the trajectory of grass and shrub abundance is similar to that of other scenarios (Figure 5.23). A comparison of grass abundance between the transition scenario, low disturbance probability/low recovery rate and high disturbance probability/high recovery rate shows that the grass abundance reaches similar levels of equilibrium in the three situations. The low disturbance probability/low recovery rate scenario has larger fluctuations and a longer period of disturbance, while the high probability/high recovery rate scenario has many shorter smaller disturbance. The transition scenario's characteristic is in between. This is more clearly shown in Figure 5.24. For shrub abundances, all three scenarios have higher fluctuations (Figure 5.25).

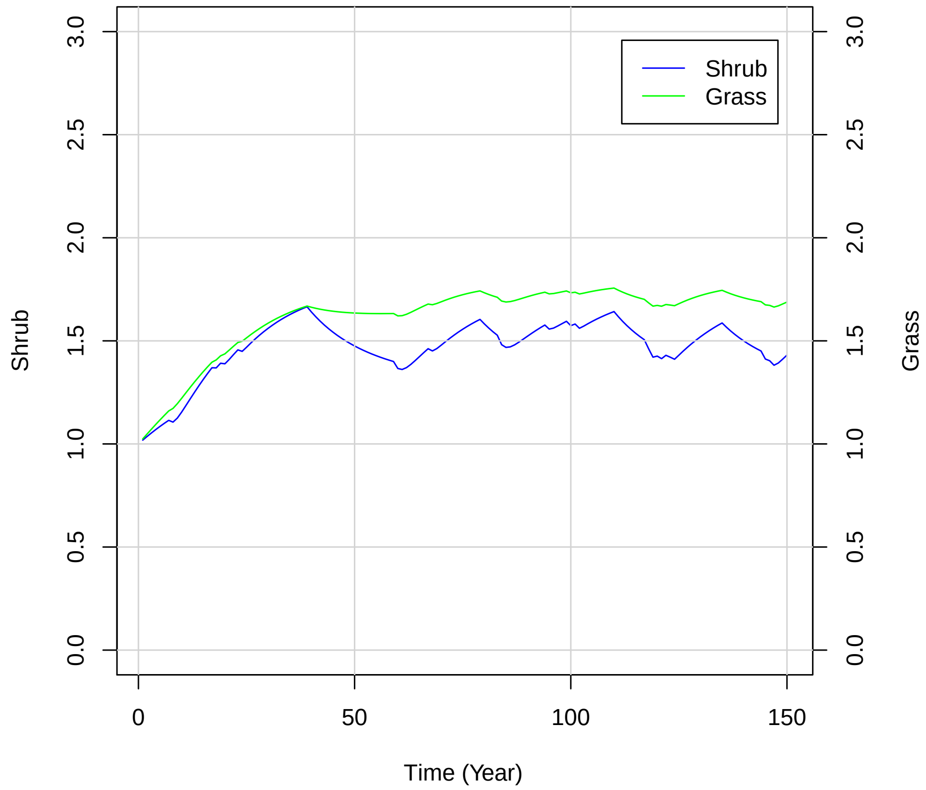


Figure 5.23: Grass and shrub abundance in a transiting system. The pattern after the transition has changed. The abundance of grass is between that of a constantly nomadic and that of a constantly ranching situation. but the pattern in general is not much different from other scenarios.

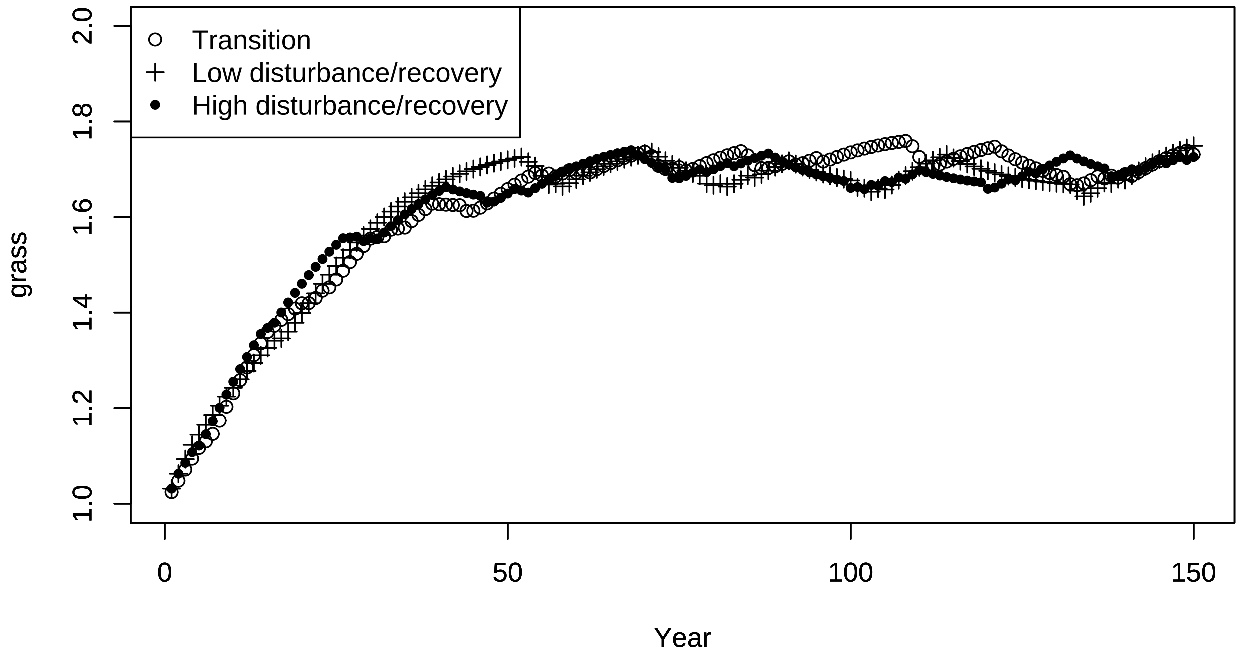


Figure 5.24: Grass abundance in high/low disturbance probability, high/low recovery rate and transition scenarios. The low disturbance/recovery rate condition seems to cause higher fluctuation in grass abundance.

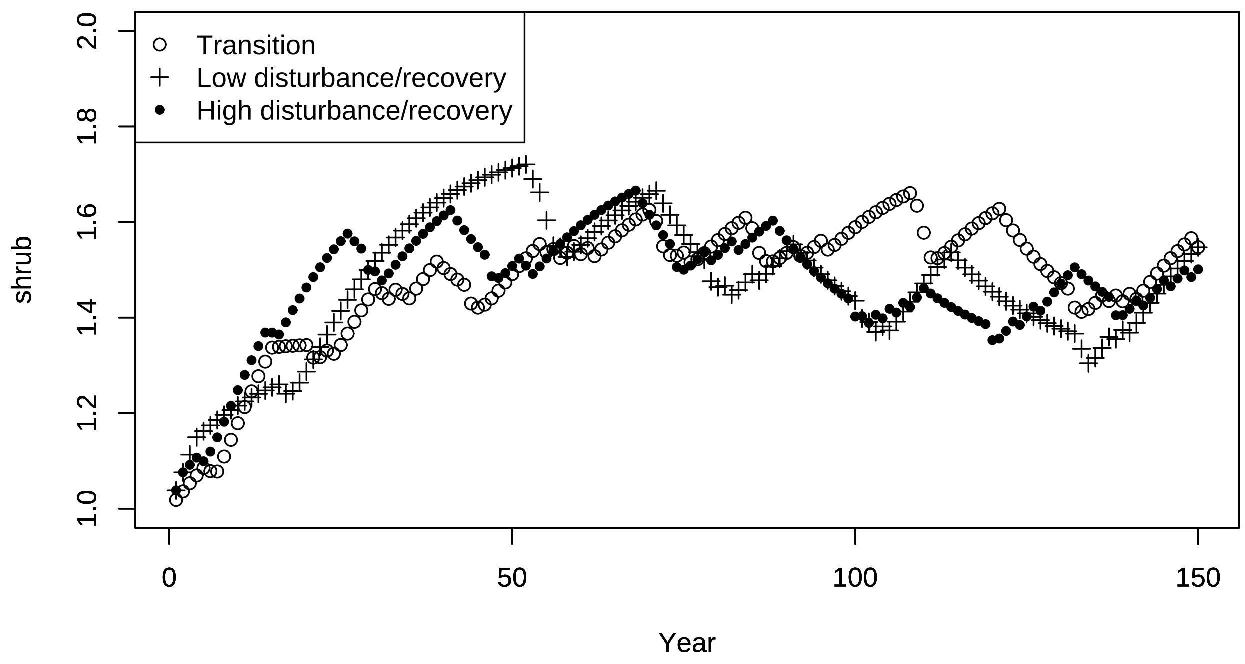


Figure 5.25: Shrub abundance in high/low disturbance probability, high/low recovery rate and transition scenarios. Fluctuations in all three conditions are similar.

The fourth scenario involves combination of the scenarios discussed above, where grass is reduced, recovery rate drops and the probability of fire risk increases. The result is shown in Figure 5.26. It can be seen that the system eventually reaches a point where the grass/shrub ratio is close to 1:1, but the grass and shrub abundances at the maximum and the equilibrium are apparently lower than in other scenarios. The impact of disturbances is more pronounced in the early period. The parameter settings are as follows:

```
g:grass_quantity 0.5
w:shrub_quantity 1
r_{g}:growth_rate_grass 0.09
r_{w}:growth_rate_shrub 0.11
s:grazing_intensity 0.38
c_{wg}:competition 0.16
c_{gw}:competition 0.16
c_{gg}:competition 0.3
c_{ww}:competition 0.3
e_{g,w}:disturbance 0.1
e_{l}:livestockdisturbance 0.1
c_{e}:recovery_rate 0.75
cl_{e}:livestockrecovery_rate 1.2
c_{f}:fire_risk 0.01
years 150
distprobab 0.3
```

The fifth scenario simulates increasing population pressure in a ranching practice setting. The result shows that at the end of the simulation period shrub species have advantage in the system (Figure 5.27).

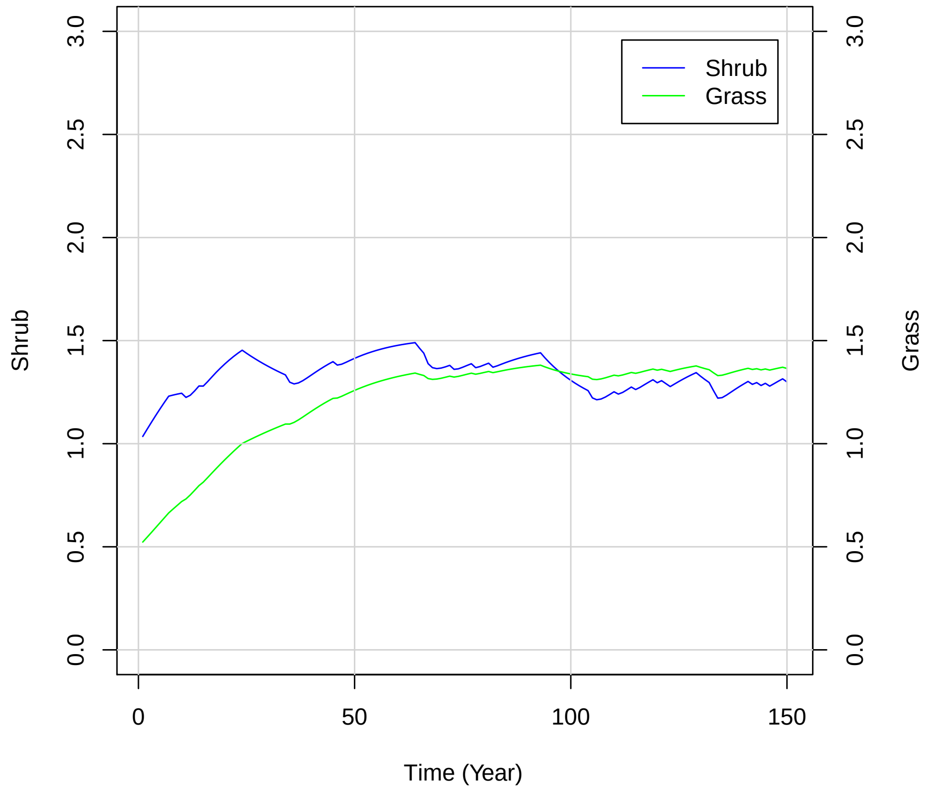


Figure 5.26: Grass and shrub abundance in a combined scenario with less initial grass abundance, higher fire risk and in a transforming system. The grass abundance is evidently more significantly impacted than the shrub abundance.

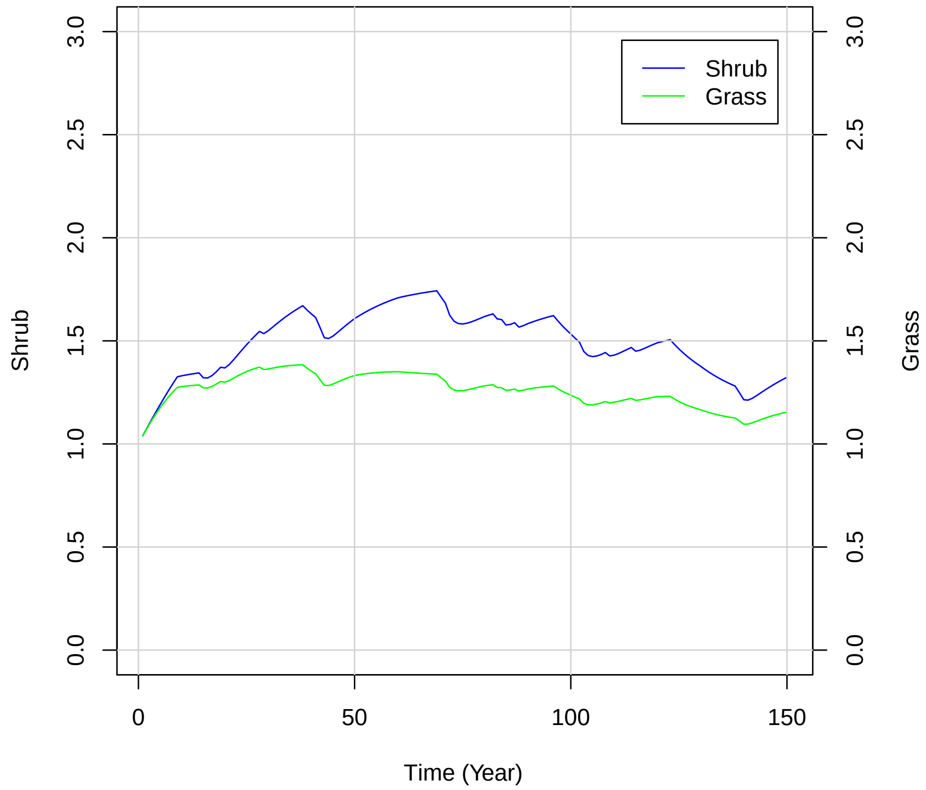


Figure 5.27: Grass and shrub abundance in the context of increasing grazing intensity. The effect of grazing is pronounced in grass abundance. Shrub gains relative and short-term advantage as the grazing pressure on grass is intensified, but is still subject to decrease due to grazing.

5.5.3 Alternative model constructions

By changing the amount of forage from a portion of available grass and shrub to a given constant value, and using parameters based on the parameter set of the “null” model, it was found that in this construction the system arrives at a similar domain of attraction, but the availability of shrub is more significantly influenced by the level of grazing. The system also has less fluctuations due to disturbance before it reaches the equilibrium (Figure 5.28). The value of grazing intensity has an effect on the trajectory of grass-shrub value pairs and the position of the equilibrium.

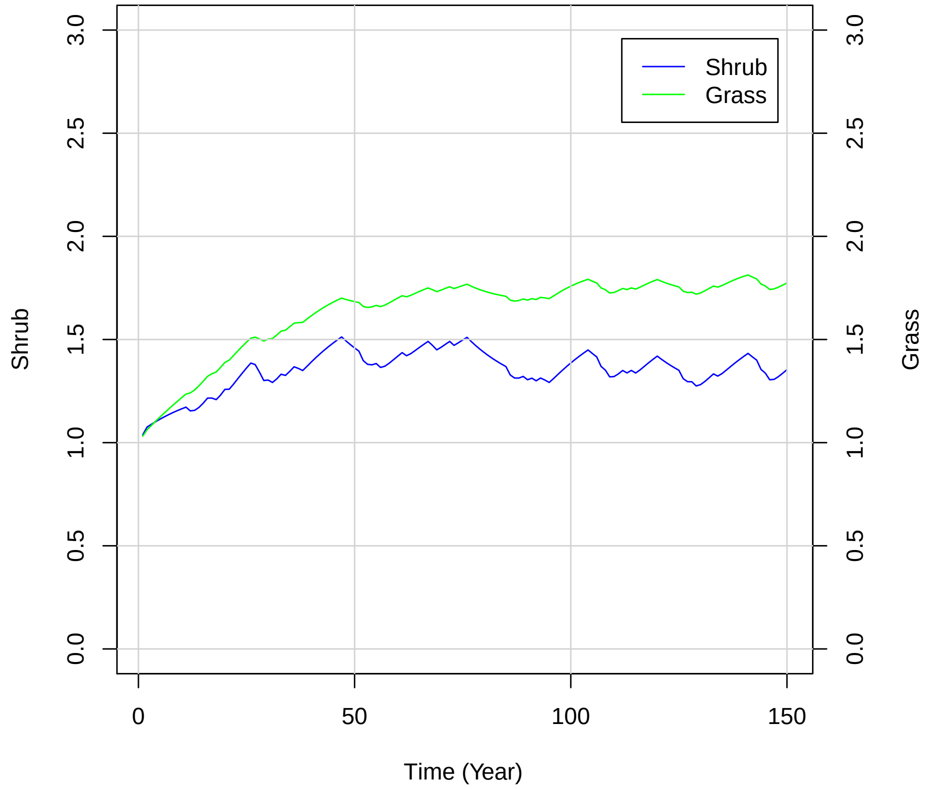


Figure 5.28: Grass and shrub abundance under the constant and equal grazing level. Grass shows relative advantage in recovery rate.

Another alternative tested was to set the initial abundance of grass or shrub to 0, while the other parameters are those of the null model. In both situation, the other vegetation had an almost monotonic increase at the beginning. After reaching a certain value the influence of disturbance began to pronounce itself, and the abundance fluctuated around the value. Grass vegetation reaches the equilibrium value later and the value is higher, possibly due to lower growth rate of grass and less impact of disturbances (see Figure 5.29 and 5.30).

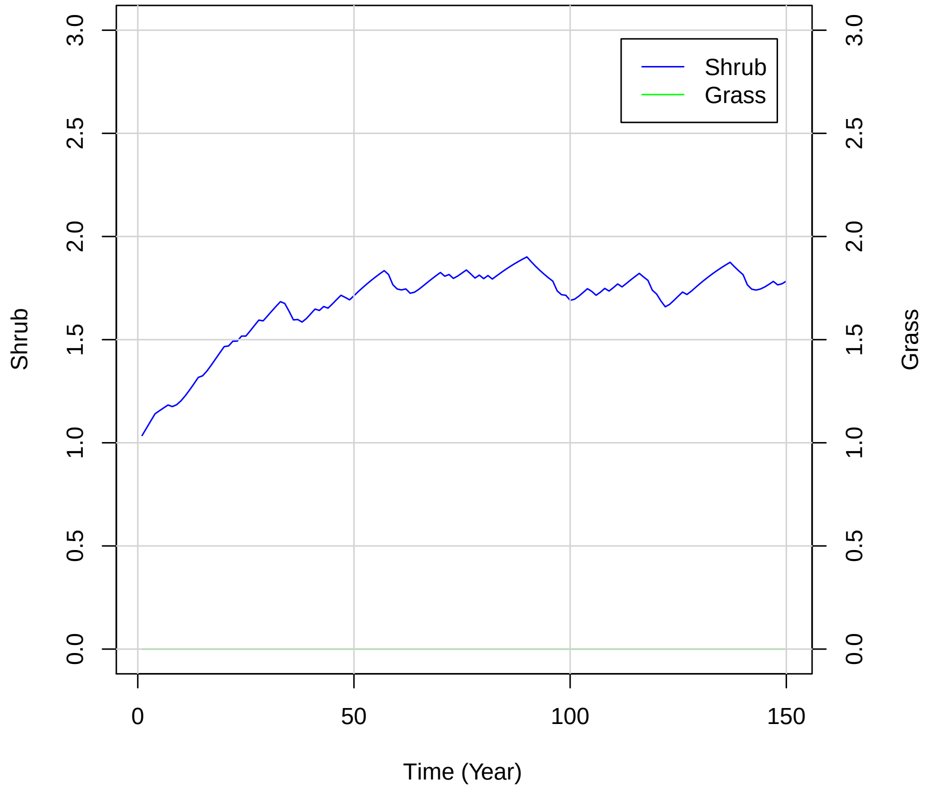


Figure 5.29: Shrub abundance without grass existence and competition. The result is higher abundance. The fluctuation pattern is not significantly changed.

The third alternative is to set the interspecies competition coefficient c_{wg} and c_{gw} to 0. The simulation result shows that the equilibrium level is higher than the null model, and more randomness around the equilibrium can be observed (Figure 5.31). If the disturbance level or fire risk increases, the trajectory of grass and shrub abundance compared to the similar scenario with interspecies competition also has more variation, as Figure 5.32 and 5.33 shows.

Finally, assuming disturbances do not affect livestock numbers and grazing level, the parameter livestock disturbance was set to 0. The shape of the resulted curve is similar to that generated by the "null" model. But the frequency of fluctuation of vegetation abundance before and in the

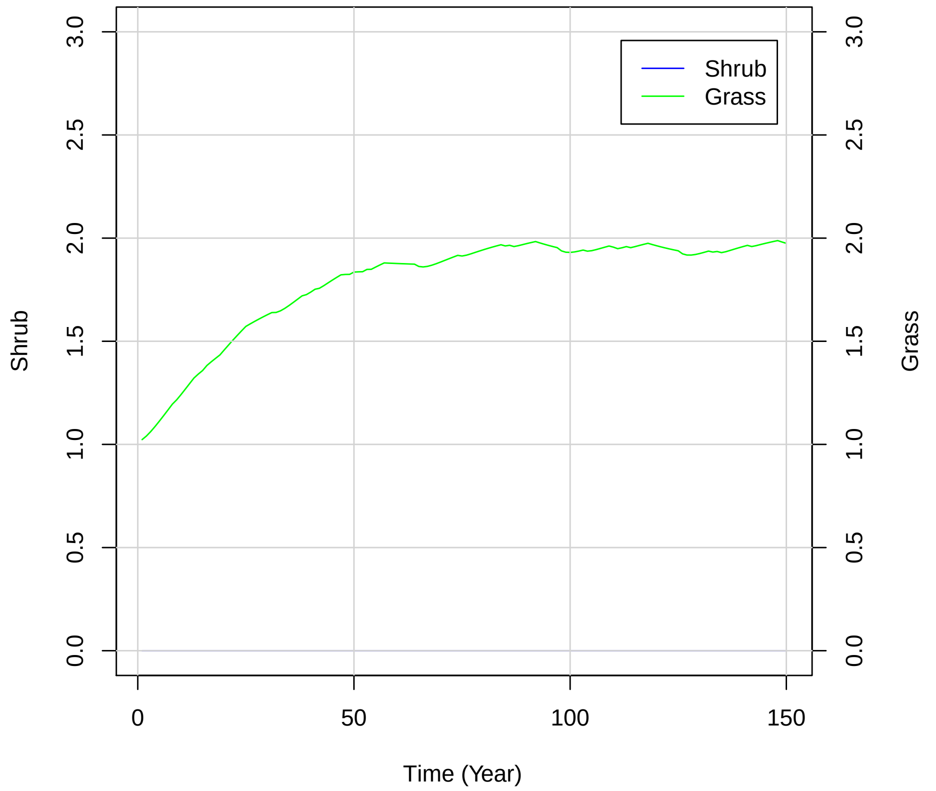


Figure 5.30: Grass abundance without shrub existence. Fluctuation due to stochasticity is very limited.

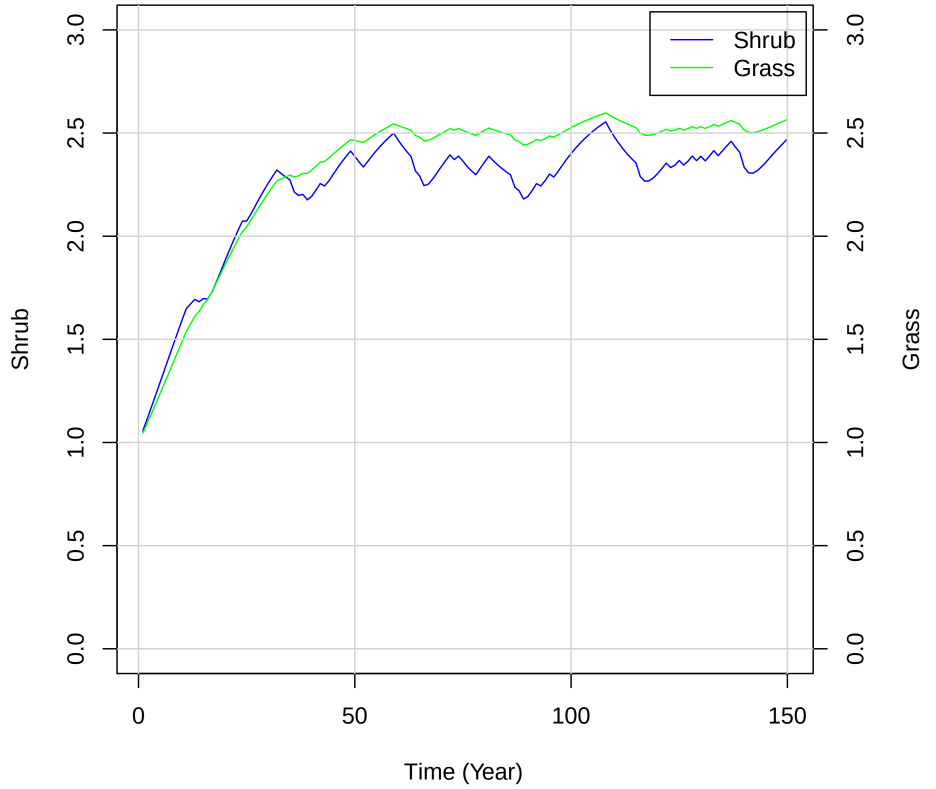


Figure 5.31: Without interspecies competition, the equilibrium reaches a higher level, but the impact of random disturbances is more pronounced.

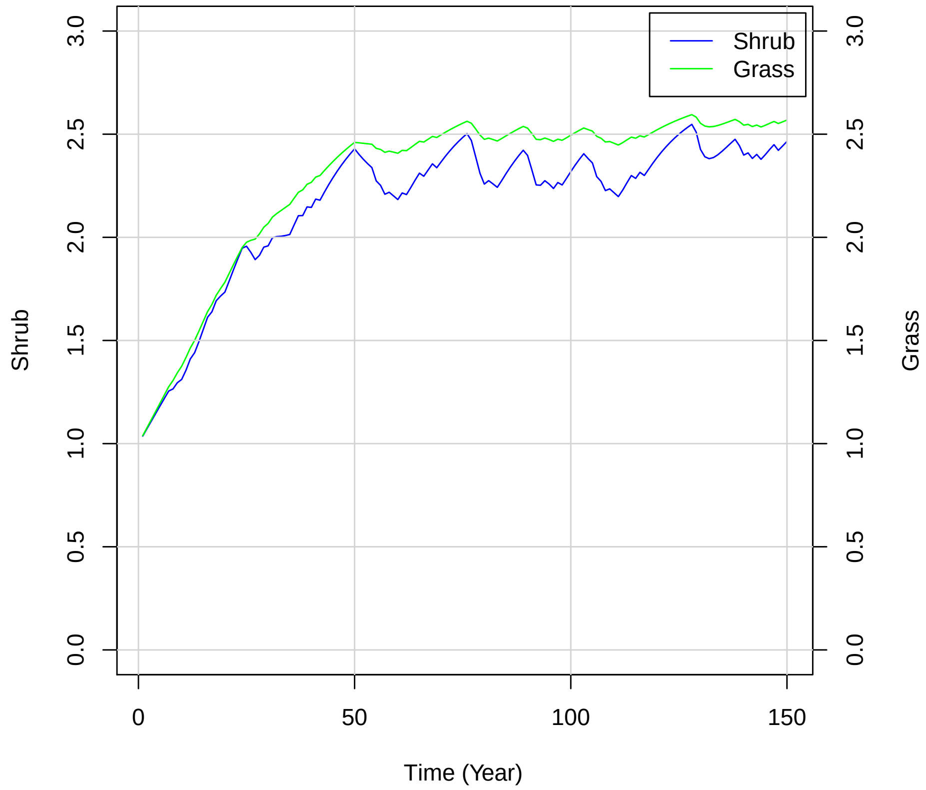


Figure 5.32: No interspecies competition, with disturbance level = 0.4. Increasing disturbance level has limited effect without interspecies competition.

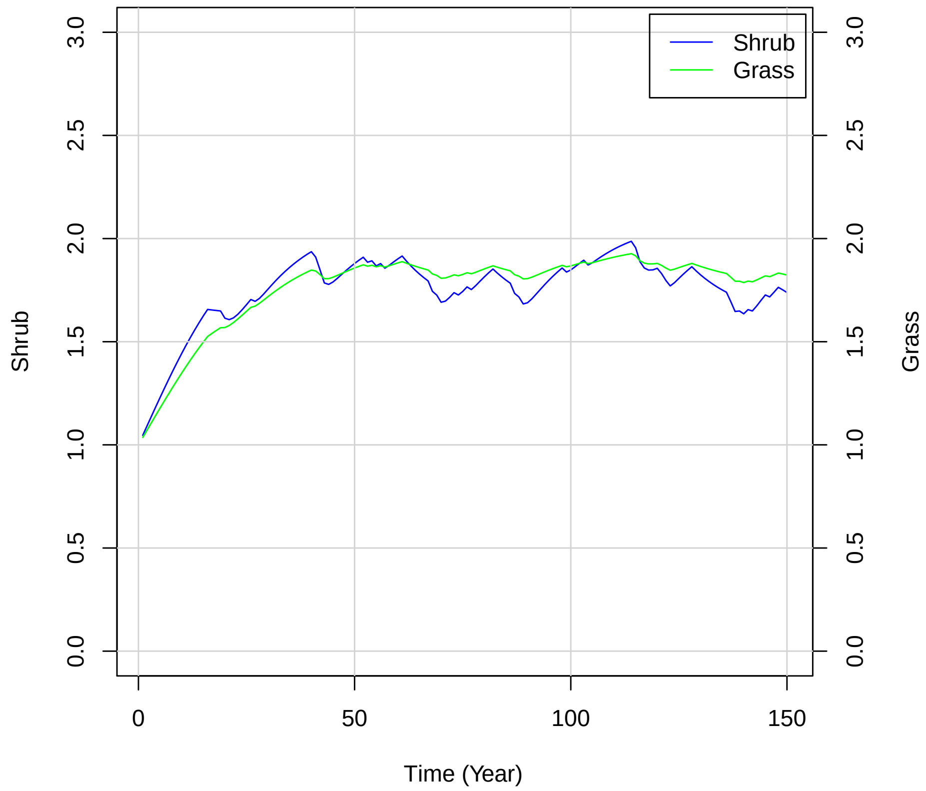


Figure 5.33: No interspecies competition, with fire risk = 0.01. The abundance level at which the system enters equilibrium is lower compared to that when fire risk = 0. Grass and shrub abundance are similarly influenced by fire.

equilibrium has increased (Figure 5.34).

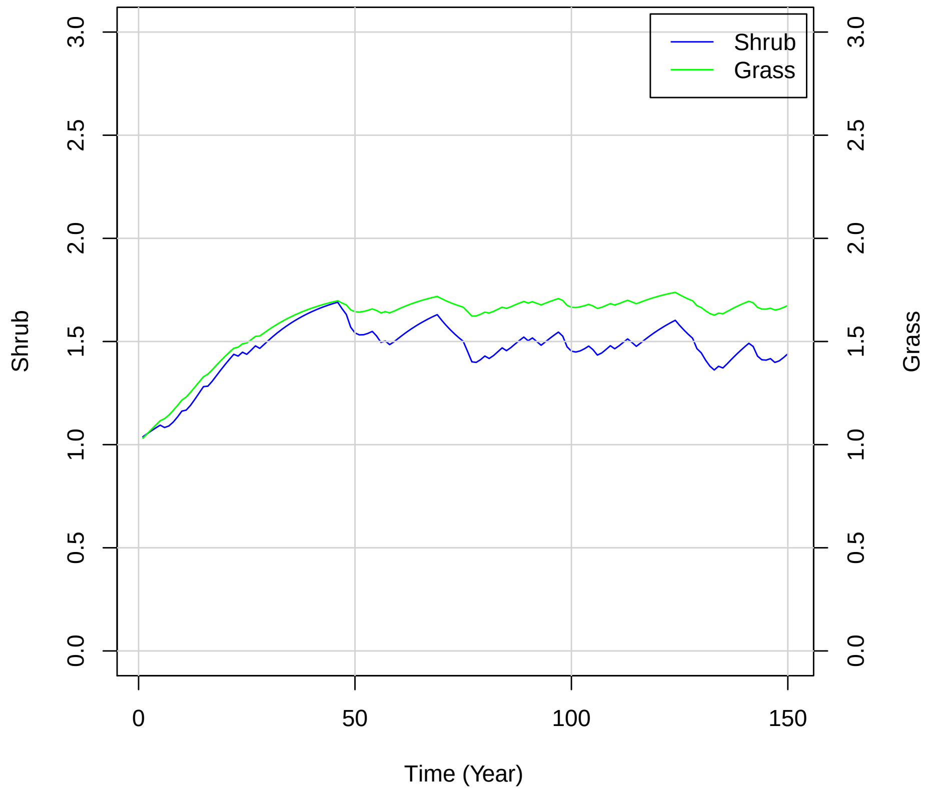
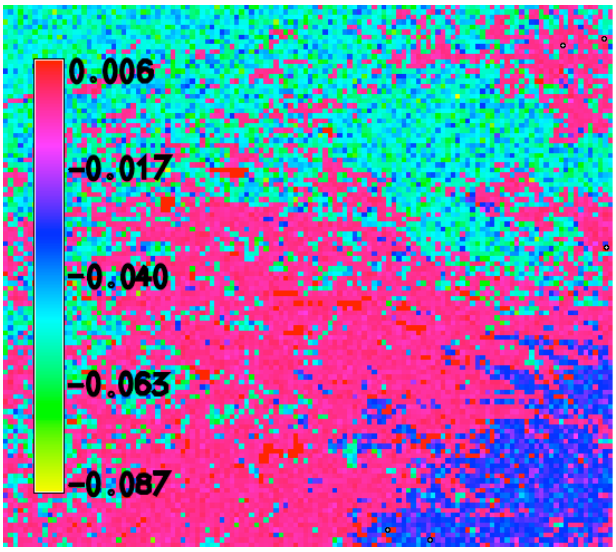


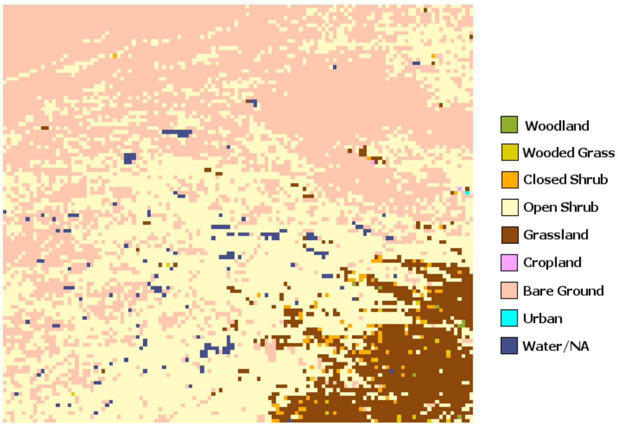
Figure 5.34: Grass and shrub abundance trajectory when total grazing intensity is not influenced by the livestock population. The fluctuation of grass by disturbance is more pronounced.

5.5.4 Spatialised model

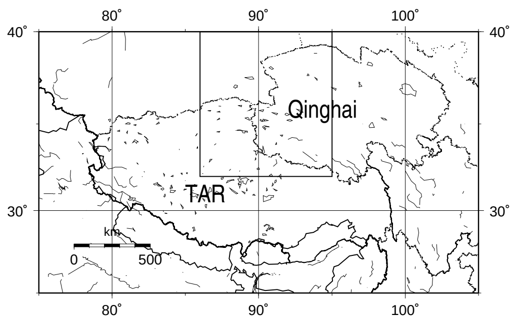
The land cover types used in the construction of the model (see Section 4.6 turned out to have a impact on the abundance change of grass and shrub. In most cases, the land cover type determined the level of abundance changes, but there were also cases in which small patches surrounded by other land cover types had changes similar to the surrounding pixels rather than the characteristic changes of its own land cover type, suggesting that the changes can spread through space. Pixels around water patches showed more decrease due to more grazing taking place around pools and lakes in model design. In Northern Tibet, despite the fact that the initial abundance of grass is lower and competition from shrubs higher in open shrubland than in grassland, the decrease of grass at the end of simulated period is higher in open shrubland (see Figure 5.35). The land type “Bare Ground” tended to have the highest level of decrease due to increased competition caused by limited resources. The pattern is consistent for long-term changes, while in the short term the trend is more complicated. In the first few years of simulated period, the changes of abundance are not significantly different between land cover types, but differences become more pronounced in later periods. The change in shrub abundance is similar to that of grass abundance. In short time periods, however, shrub abundance may have larger fluctuations.



(a)



(b)



(c)

Figure 5.35: (a) shows the simulated changes in grass abundance in northern Tibet, with land cover types shown in (b). (c) shows the geographic location of the images.

Chapter 6

Discussion

In this chapter issues that emerged during the study are discussed in more detail in order to reveal their implications for the area's resilience and other sustainability issues. The factors include El Niño events, cross-scale interactions and the largely completed pastoralism transformation in the area. The impact of difficulties in obtaining data on the study's assumptions and results is also discussed here.

6.1 Effects of El Niño phenomenon on resilience

It was found that El Niño events are a significant factor influencing the area's climate, and vegetation responses as well. The study of the impact of recurring El Niño events on resilience is a necessary part of the resilience study. This section also discusses the complexity and challenges of modelling of the phenomenon.

6.1.1 Frequency of El Niño and frequency of disturbance

In the model used in the study, the disturbance was assumed to take place at a relatively high probability. The expectant frequency, according to the characteristic of the generalised extreme value distribution, is around one new disturbance every 4 to 5 years for the null model. This reflects the idea that drought related disturbance caused by El Niño is a major type of disturbance on the plateau. Some studies suggest that in the 297-year period from 1690 to 1987, there were 87 El Niño years (Yang et al. 2000). Assuming that each event on average lasted for 2 years, that equals one El Niño event every 5-7 years. Thus the probability model of disturbances were parametrised as in the model. However, from record over the period from 1803 to 1987, Quinn et al. (1987) concluded that the average interval between El Niño events was 3.8 years. Sea surface temperature records show that in recent years the occurrence of El Niño is more frequent, as the 6 events in the period from 1986 to 2000 show (*NOAA/PMEL/TAO - What is an El Niño (ENSO)?* n.d.). At present it is still not clear whether the increased report of El Niño events reflects a genuine increasing trend or is merely due to an increased susceptible population in coastal areas and improved observation network and report technology (Quinn et al. 1987). Nor is it clear whether El Niño events will become more frequent in the future. But the simulation of such a scenario can be realised by increasing the probability parameter in the model.

Besides El Niño there are other sources of disturbances as well. However, disturbances from these sources take place in a more stochastic manner, thus the model does not simulate them directly. The disturbance in the model does not disappear immediately in the following time step after it occurs, but decays in a exponential manner. It is hoped that some disturbances caused by sources other than El Niño can also be simulated by the decayed disturbance. This is for the sake of simplicity of the model. The probability of disturbance and the rate of decay were parametrised with the simulation of the whole area in mind, and are aggregated values. In a spatial-explicit model, the frequency of disturbance for a location or a cell should be lower, while the rate of decay depends on the land use type, position and neighbour location or cells.

6.1.2 Accumulated effects of El Niño on existing disturbance

In the model, new disturbances and decaying old disturbances are added up to simulate the combined effect of multiple disturbances taking place in the same time step. However such linear addition may not reflect the fact that El Niño events do not only constitute disturbance, but also enhance other disturbance factors in a non-linear manner. For example, there is evidence showing that reduced precipitation in El Niño events in Inner Mongolia can cause rapid increases in the population of rodents, thus strengthening the disturbance caused by these species (Zhang and Pech 2003). As Tibetan and Inner Mongolian grasslands are similarly influenced by El Niño events, it can be expected that similar fluctuations of rodent population may happen on the plateau. On the other hand, the effect of El Niño, namely reduced temperature and precipitation in the summer, may also enhance drought disturbances by increasing the area impacted and lengthening the period for the vegetation to recover from the drought. The impact on resilience may be more significant if a series of El Niño events take place in a short time period.

El Niño events not only increase the intensity of drought, but also make drought disasters more frequent. Climate statistics have shown that drought frequency worldwide is linked to ENSO events, while many significant drought disasters, including those in Tibet, tend to happen in the second year of El Niño events (Dilley and Heyman 1995). On the Tibetan Plateau, aside from reducing precipitation in summer, El Niño events cause more winter precipitation in the form of snow. This part of precipitation can hardly be utilised by vegetation, but often impedes germination of grass in the next spring, causing a loss of the viable seed bank. Moreover, the resulting local shortage of herbage causes loss in livestock, or alternatively the grazing pressure is increased on pastures less impacted by the means of migration of pastoralists and livestock, causing a migrated, cross-scale impact.

These effects bring greater uncertainty to the modelling for resilience studies. If seed bank and water availability are considered as slow variables that determine the key functions and behaviour of the system, it is still difficult to tell what is the combined impact of drought and recurring El Niño events. What makes the question even more complicated is the non-linear and cross-scale nature of El Niño events' implications. For the purpose of the study, the impact of El Niño events can be qualitatively studied by adjusting the parameters of the model, which is probably sufficient for the need of simulating dynamics. If a spatially explicit model is used, it is necessary to understand the spatial heterogeneity of responses of different locations to the events, considering the availability of local water source, land use types and management. It would be desirable to explicitly simulate the spatial and temporal impact of El Niño events in order to reveal how it influences the mechanism of the system in question, but that is beyond the scope of this thesis.

6.1.3 Modelling El Niño

Given the non-linear and cross-scale nature of El Niño impacts, it is easier to model the phenomena in an aggregated way rather than making it spatially and mechanically explicit. In this study, the model simply regards El Niño events as an areal disturbance and does not distinguish it from other disturbances. Because the model has no spatial dimension and is largely qualitative, doing so avoids bringing unnecessary complexities into the study. As the information on the quantitative impact of El Niño on the plateau is still not available, it is not appropriate to try to quantify the individual impact of this disturbance as well as many others'. However, the researcher does assume that the collective effect of these disturbances can be represented by the combination of stochastic occurrence of new disturbances and decaying old ones, in the belief that this pattern reflects how vegetation responds to disturbance and recovers from it. The non-linearities of El Niño, and possibly other disturbances in this view emerge as the combination of mathematically tractable processes, yet capable of representing discontinuity and surprises, making the simulation of disturbances in a complex system solvable. In a study of overall resilience of a complex system, such assumption and simplification may well be necessary, in the context of current understanding of socio-ecosystem processes and available data.

There have been attempts to simulate El Niño events with general circulation models (GCM). However, the complexity and effort involved in such studies merit a standalone research project, if not many related projects. Thus in this study GCMs cannot be used to provide a more accurate estimation of El Niño's impact on climate. The researcher's climate understanding has been informed by these models, which can also provide information on possible climate scenarios in the future and inform resilience studies.

6.2 Means and implications of scenarios

Various scenarios were designed and simulated by changing the expression or parameters used in the model. The purpose was to qualitatively identify the impact of changed environment, policy or management styles, and to inform the design of a more quantified, spatially-explicit model. A default scenario with light grazing was first simulated to provide a reference. If the default scenario is altered by changing the initial abundance of grass or shrub, given adequate period of simulation, the ratio of grass and shrub at the end will be close to 1:1. This is because the model has chosen a relatively high intraspecies competition coefficient, which limits the highest abundance level a species can achieve and partially limits the highest possible rate of growth. In this parameter set the value of the interspecies competition coefficient has no significant role because the limiting effect of intraspecies competition will become manifest earlier. Considering the fact that on the Tibetan Plateau, especially its northern and western part, shrub and grass communities have relatively clear borders, and are limited mainly by low nutrient and water availability, the high intraspecies, low interspecies competition assumption seems to be valid. But both coefficients can be turned down to make effects of other factors more pronounced.

The climate change scenario simulates the influence of a possible climate change event, in which the vegetation's recovery rate is lower and the probability of disturbance higher. The effect of increased disturbance can be observed early in the simulation. But the effect worth noting is that after grass and shrub abundance reach an equilibrium level their trajectory is confined to a smaller space compared to the default scenario, especially for that of grass. In longer term simulations with this scenario the effect is more pronounced. This may indicate that in this scenario the abundance of shrub and grass enter a domain of attraction with high resilience, yet the outcome of reduced vegetation cover is certainly not desirable. The results of other scenarios also suggest that increased fire risk may impact grasslands severely.

The urbanisation scenario is simulated with the initial abundance of grass set to half of that in the default scenario, while the grazing intensity is lower. This is to simulate urbanisation in the area. Due to the effect of intraspecies competition, grass at the beginning was able to increase at a faster rate. Eventually the abundance of grass exceeds that of shrub, as the latter is impacted by disturbances and intraspecies competition. However, this simulation assumes that grass on the remaining land faces the same intraspecies pressure as before, which is not realistic. The reduced suitable land for growth will cause increased intraspecies competition. With this in mind, the simulation result is given in Figure 6.1. It can be seen that grass is still able to increase from a lower level, but the balance is established at a smaller abundance for grass.

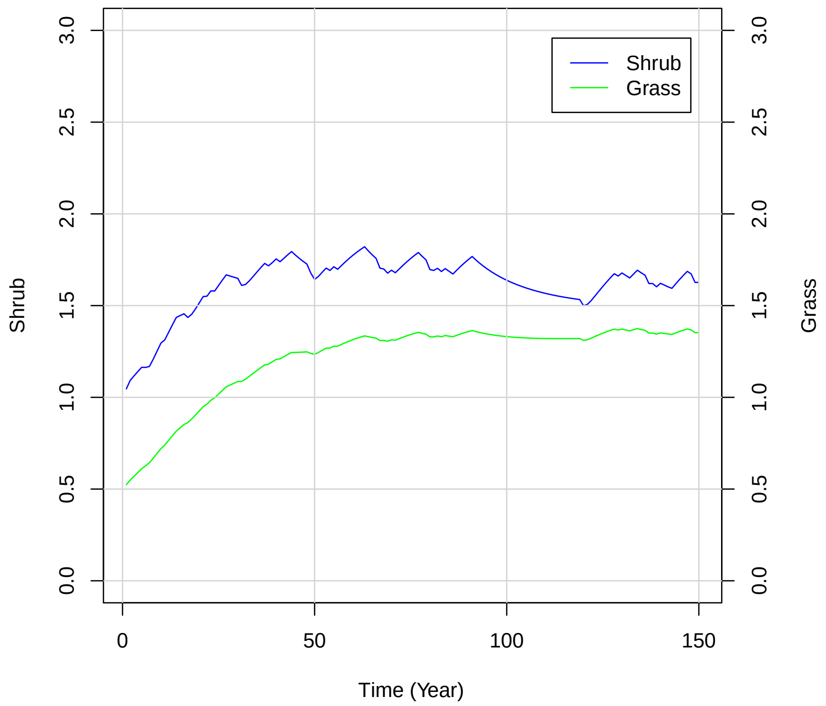


Figure 6.1: Urbanisation caused scenario, with reduced grassland and increased intraspecies competition of grass

The transition scenario attempts to simulate the influence of transforming nomadism into ranching practices, in the process of which, both the probability of disturbance and the recovery rate are reduced. The comparison of grass and shrub abundance dynamics before and after the transition shows, as expected, that the low disturbance probability/recovery rate phase shows longer periods of disturbance and larger fluctuations in vegetation abundance, while the high disturbance probability/recovery rate phase shows a series of short, smaller fluctuations. The final abundance of grass and shrub is not significantly different in different practices. However, this simulation has taken a very partial view on the impact of the transition. When nomadic pastoralism is transformed to sedentary pastoralism, the grazing intensity on a pasture will increase, while a part of the grazing pressure originally on shrub will be transferred to grass. In ranching practice the grazing intensity on grass and shrub does not respond to the sum and proportion of their availability, as the model implies, but is maintained at a certain level as long as enough herbage can be provided by the grassland. Ranchers may improve their grassland so grass has higher growth rate ($r_g = 0.15$) and less intraspecies competition. Considering these factors, a simulation can show that in ranching practice grass abundance can reach a high level within the ranch and eliminate shrub even if little management of shrub is implemented (Figure 6.2), assuming the high growth rate of grass can be maintained. The trajectory of grass and shrub, assuming only minimum grazing remains, is similar to that of the default scenario. The fifth scenario can be regarded as the continuation of the fourth, but different in that grazing intensity is constantly increasing, causing the grass to be replaced by shrub.

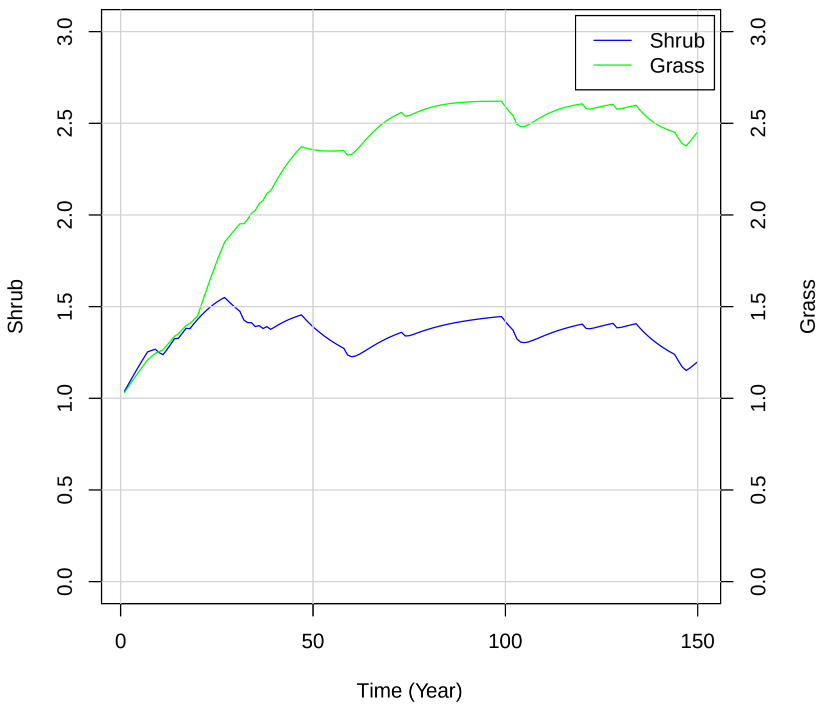


Figure 6.2: In ranching practice, the abundance of grass and shrub, provided that the pasture is improved to support a high growth rate of grass

6.3 Discussion of results and resilience

6.3.1 Frequency of disturbance and persistence of vegetation

The simple statistics on remotely sensed images of NDVI suggest that in the second year of El Niño events vegetation is negatively impacted by reduced summer precipitation and temperature. As discussed previously, this has an impact on the viability of seed bank and water availability, which are the slow variables of the system. Thus the frequent occurrence of El Niño will impact on the ability of vegetation to cope with other disturbances and maintain key functions. The system's resilience is then influenced by how frequently El Niño events occur. Comparing historical records of El Niño events taking place before 20th century and that of recent 50 years, especially in the last 10 years of the 20th century, it appears that El Niño events have occurred more frequently. Although this may be related to the fact that recent years' records are more complete, the possible implications for the system's resilience should not be overlooked. Considering the trend of global climate change, it is very likely that the impact of reduced precipitation will become more intensified. The DFA result on the area's average NDVI further suggest that the long term disturbance trend is positively related to past disturbance, suggesting that disturbance impacted areas tend to have more disturbances in the future.

On the other hand the persistence of NDVI anomalies throughout 1982 – 2001 suggests that although locations having long persistent positive or negative values are rare, on a smaller time scale many pixels have long negative trends in the period from 1992 – 2001, suggesting that the recovery of vegetation after disturbance is hindered by recurring disturbances. It can be argued then that the frequently occurring disturbances in 1990s has reduced the system's ability to recover. The researcher's field observations in Qinghai in 2004 and in Tibet in 2005 has witnessed the degradation of grassland and the forming of dunes in heavily disturbed areas, which support the argument. Some areas of the system have entered a undesirable state with an increasing resilience. To revert such a state will require a change in the slow variable, in this case climate trend, as well as long-term management of a vast grassland, which is difficult to achieve under current conditions.

6.3.2 Resilience of vegetation and that of the system

The study has focused on the change and trends of vegetation on the plateau represented by the readings of NDVI values from remotely-sensed images. As a result, the analysis and modelling has concerned vegetation productivity and viability. From previous sections it can be seen that qualitatively a large portion of the area is heavily disturbed and susceptible to further disturbances, this threatens resilience in areas that are in a favourable condition, while increasing resilience in disturbed areas, causing the loss of key components and functions that is hard to reverse. Transforming nomadic pastoralism to ranch style practices is predicted by the model to be able to help establish conditions favourable to pastoralism within the ranch while maintaining a reasonable balance of grass and other vegetation, given that wildlife communities are intact and shrubs are controlled. However these two conditions cannot be met without considerable investment and careful planning. The Tibetan Plateau's poor nutrient condition and composition of species determine that grass growth rate cannot be improved without external sources of nutrient, but higher nutrient levels may also trigger invasion of other species and loss of biodiversity. As the population on the Tibetan Plateau increases, the pressure will require more pastures to be turned into ranches, which will intensify the competition between ranches and need for wildlife conservation over water sources, migration paths, and so on. Ranching practice can also improve the resistance to short term disturbances, but in the longer term dealing with more frequent and intensified disturbances will require the flexibility and built-in negative feedbacks of nomadic pastoralism. If pastoralism is to be maintained as a part of Tibetan culture and livelihood, the mobility associated with nomadic pastoralism is still required. The most important objective of adopting ranching practice should only be facilitating infrastructure and institution construction, in order to achieve a society that no longer depends on pastoralism to provide livelihood and income. Nevertheless, the time and financial cost of this goal seems to be prohibitive.

Using vegetation as a surrogate of resilience was the major means of research in this study, and is justified by the fact that the grassland socio-ecological system is organised around pastoral production, whose base is an adequate supply of herbage. However, the viability of the economy in this system is not solely determined by vegetation, as pastoralism now is still a source of livelihood rather than a source of disposable income. The other aspect of the system's economy is still largely detached from the natural production system. Many other studies of socio-ecological systems also focus on natural production, but this approach inevitably loses the sight of economic diversity and the implication of institutional changes that do not involve use of natural systems. This is especially true in the context of the area's changing urban environment and policies. Issues such as the changing mind set of the younger generation, the diversification of the urban labour force, and the flow of goods between urban areas and pasture land should be addressed if a holistic resilience assessment is to be carried out. However only a simple discussion can be given here. In counties and towns near the Qinghai-Tibet highway and railway, it is a common phenomenon that more and more people of the younger generation are not willing to carry out their pastoral duties in the family. Instead, they are pouring into the cities to work as barterers and construction workers, causing the loss of pastoral memory. On the other hand, pastoralism products from Tibet are at a disadvantage in the competition with products from Inner Mongolia, other parts of China, and even abroad. This may lead more pastoralists to abandon pastoralism as an economy. From this perspective, using the transformation to ranching to accelerate construction of new towns and infrastructures is a proper measure, as long as the new system's function can be maintained.

6.4 Scale issues and sustainability

The model can simulate the change of states and resilience to some extent. However, it is difficult to predict the impact of cross-scale interactions and to look at the whole system's sustainability from a multiple-scale perspective. A series of challenges present themselves before the multi-scale problems can be correctly perceived. These challenges include the ignorance of complex human-environment system interactions, the mismatch between human management practice and the biogeophysical scale of the natural system, and the multiplicity of actors and interactions causing multiple attitudes towards various cross-scale interaction (Cash et al. 2006). A solution to these challenges is to identify common social and institutional responses, such as multi-level institutional interplay, co-management by government and local communities, and emergence of boundary of bridging organisations (Cash et al. 2006).

The model simulates a period of 150 years. In this period as has been discussed, the nomadic pastoralism practice may be more flexible in terms of dealing with surprises, while the ranching practice requires considerable external input to maintain. However, considering a larger time scale, the picture is embedded with more implications. The long-term goal of ranching practice implies that Tibet will need to establish a competitive livestock economy, which in turn needs the support of other economies and institutions, and thus calls for a diversification of livelihoods and professions. In this perspective, the current transition that is done at the areal scale seems too hasty in that it does not give local people time to develop professional education and markets to transform their society into a commercial one that is needed by such an economy. In a gradual manner, the most developed areas in Tibet can transform to ranching practice first, creating market and education systems, that will facilitate transformation in other areas. But the wholesale style of transformation requires vast investment in infrastructure construction, and there is not an adequate supply of talents to support a healthy modern livestock economy, thus in the long term it is difficult for this system to be sustainable. Nomadic pastoralism in the long term is also facing the dire challenge of loss of social memory about this unique production system. As the younger generation move away from the land, very few people are willing to go back to traditional pastoralism now that they have found better ways to support themselves and their families. In maybe a few generations nomadic pastoralism may diminish in this case, which again calls for social support for people who become vulnerable in this process.

Another often mentioned question is that whether a system's sustainability is costing or enhancing that of the larger system. This involves more complex interactions at national and regional scales. A ranching system will have more dependency on local water sources, which may influence water availability and ecosystems downstream. The competitiveness of Tibetan pastoralism may have impacts on other provinces' similar sectors. These larger scale problems do not influence the conclusion about whether the system is sustainable, but may influence decisions from leaders of higher level institutions on whether a policy for sustainability should be implemented.

6.5 Limitations by lack of data

In the study there was difficulty in obtaining ground and social/economic data, which brings some limitation to the analysis in the study. The first difficulty was brought by the lack of a detailed meteorological record, as the area's record is not openly accessible except that from Lhasa station. As a result the impact of El Niño cannot be thoroughly discussed, because the spatial pattern of its impact cannot be established. The relationship between climatic conditions and vegetation responses was also vague because of lack of data. These problems were partially mitigated by using remotely sensed GLDAS precipitation and temperature data, although the data is generated on the premise of a series of remotely sensed data and land surface models, and is subject to inaccuracies and errors.

Due to complexity brought by the situation in TAR in early 2008, and the researcher's identity as an international student studying in the United Kingdom, the researcher was denied fieldwork access to the area by the local authority. This created a series of data acquisition problems. The researcher had planned to gain a qualitative understanding on nomadic practices and ranching in Tibet, as well as to collect land cover data to validate the land cover map generated by remotely sensed images. Being denied such access, the researcher had to resort to his previous experience in Tibet and limited news report about the area's reform. Because the government in the study area has already managed to transform most of the herdsmen into sedentary pastoralists, the organisations of production and trade may have changed, as well as the lives of the remaining nomads. Land cover data derived from remote sensing imagery are often too generic, if not inaccurate, in reflecting the actual vegetation types on the ground. The actual vegetation distribution is not as clearly delineated as the land cover classification suggests (Chopping 1998). Therefore some assumptions and scenarios based on the researcher's understanding gained a few years ago and from remote sensing may not reflect the actual situation in the area. The social-economic institutions of the area is another important sector that deserves a closer study as it now directs how local people manage their livestock and how they obtain economic support. They are also crucial in understanding how people in the area cope with disasters and surprises. The lack of data from this perspective forced the researcher to use a model dealing solely with natural production and infer economic performance of the system.

6.6 Pastoralism transformation in the area

In 2004 the TAR started a pilot project of transforming nomadic pastoralism into sedentary livestock farming. The full-scale project began in 2006 and has largely transformed the way pastoralists live in most areas of the TAR as well as areas in adjacent provinces. Despite the criticism that doing so may harm the unique nomadic culture, it must be realised that Tibetan pastoralists have the right to enjoy improved infrastructure, supplies of electricity and running water and accessible medical care and education, which are very difficult if not impossible in nomadic conditions. This is indeed the rationale behind the policy. However, it is also necessary to acknowledge the limitation imposed by the natural conditions in the area, including relatively low productivity, frequent natural disaster and limited and uneven water availability. The problem is exaggerated by increased population pressure due to the improved economy and livelihood and an increased immigration. If population pressures are not controlled, the system cannot be sustainable no matter what production system it adopts.

Now that the system is transformed into a new state dominated by controlled environment, it is not possible to deliberately return to the old situation where human population and livestock are kept in check by frequent natural disturbances. In the new pastoralism system, the provision of livelihood and income must be balanced with the ecosystem's need to cope with disasters and recover. This requires the environment managers to be able to perceive possible crises, to take actions accordingly, and to evaluate the effects. Needless to say, this is much more difficult than management in nomadic culture, in which the control is largely in the Nature's hand. The new system is also less resilient in terms of maintaining a pastoral social-ecological system. Nevertheless, to adapt to changed environment, it is often necessary to embrace altered core values, as societies that fail to do so cannot adjust themselves properly. The new system provides possibilities to adjust the system to a drier climate and increasing population. In this sense, sedentary pastoralism may be more resilient in terms of the whole society rather than concerning a particular style of production. Moreover, the new system may imply a development path that has been taken by many societies in the world, which has proved largely successful so far, yet in a world with fewer disposable natural resources, this path and its underlying value system may also have to change to adapt to changing conditions. But this is a much larger question that cannot be dealt with in this thesis alone.

Chapter 7

Conclusion

In previous chapters, the researcher shows that the area is facing a series of challenges that need to be addressed in order to achieve ecosystem conservation and sustainable development. Different from previous approaches which measure indicators of the attributes of the system after disturbances, this study focused on the trend pattern of the disturbance itself and whether the system is flexible and resourceful to respond. How nomadic and ranching system meet these challenges is summarised. Thus their implications on the system's resilience can be examined to show that preserving local pastoralism and developing the area are two objectives that have conflicts. In this chapter the researcher also examines some issues that require more consideration in the reform process in the TAR. The study attempted to approach the question of resilience on the Tibetan Plateau from the perspective of vegetation state, disturbances and response, as reflected in the aims of the study. The significant influence of changing social and historical context was also addressed.

The result of Detrended Fluctuation Analysis using remotely-sensed images in the period of 1981 to 2003 suggests that the area is likely to undergo disturbance events with increased intensity in the future. Frequent El Niño/Southern Oscillation events may also have a negative impact on the area's vegetation viability. The high temperature event in northern Tibet in late 1990s had a significant impact in the trend of NDVI anomalies, while similar events may return, judging from the current climate trend of warmer climate in Tibet. Already being an arid area, these trends along with high probability of drought make it difficult to sustain a stable forage output. The global trend of climate change may enhance these events and constitutes an even greater challenge to the grassland ecosystem's functions. On the other hand, the ever-increasing population depending on pastoralism as their livelihood requires more, greater herds, which brings increasing pressure to the natural production system.

At the same time, the state-wide movement in China to embrace the market economy, improve industry structure and stimulate development in the western part of the country calls for a change in the TAR's economy if its economic gap from inner China provinces is not to be irreversibly widened. This again poses multiple challenges to Tibet's pastoralism. Pastoralism is regarded as the most feasible means of establishing a viable economy in this area, but to upscale it from a livelihood support to a source of disposable income implies increase in quantity and quality, which demands a much larger input of energy and goods into the area, and larger output from the grassland system. Already falling behind, the pastoral economy in Tibet also faces strong competition from other major pastoral areas in China, whose economy is stronger and more balanced. It is also an objective for local people to enjoy the benefit of improved education, medical care and civil engineering, which cannot be a sustainable goal if it depends so largely on aid from other areas of China.

In recent years the younger generation of Tibetan pastoralists in the area are abandoning livestock raising as a way of life. Instead, they try to find job opportunities in construction or transportation sectors in cities. Similar phenomena were seen in inner China when the Open and Reform policy was implemented in late 1970s. This in the TAR causes a loss of labour in pastoralism, and more importantly loss of social memory as the older generation cannot persuade the younger generation to stay on the pastures and pass on the knowledge about nomad pastoralism.

Nomadic pastoralism deals with natural fluctuations in weather conditions and natural productivity by keeping mobility and raising large herds as a means of insurance. This in practice involves setting up a rotation system within a group of families for allocating winter and summer pastures, and moving to another location if the pastures are deemed not suitable for supporting their herds. This system is not stable in the word's conventional meanings, as natural disasters can deal a heavy blow to the herds and reduce their number significantly. However, it can be regarded as very resilient, as each disaster-recovery process constitutes an adaptive cycle, with the key characteristics and functions of the system restored in each iteration. The pastoralists consciously build up the herd in the r and K phase of the adaptive cycle to make sure the herd is still viable after the disturbance in the Ω phase, and the resilience and options of adaptation are restored in the α phase. However, looking at the system at a coarser temporal and spatial scale, it is reasonable to say that the system in a larger adaptive cycle is in the K phase or even in an early Ω phase. The insurance measure may not be feasible in the face of more frequent and intense disturbances, and pastures are not sufficiently numerous or extensive to support an ever increasing population and their need for livestock products. In other words the ability to adapt is severely limited in the area at present, hence the resilience of the system is also diminishing. The loss of memory and local knowledge also make it difficult to identify adaptive options in the face of disturbances, further decreasing resilience.

The ranching system has been criticised as causing over-grazing and reducing mobility of pastoral communities, leading to vegetation degradation and economic failures (Richard 2003*b*). The proponents of ranching practice argue that ranching systems make it possible to establish modernised infrastructures such as a road network and an electric grid. Although this is an important effect of ranching reform, the real implication of the transformation is that, in an ideal scenario, it allows the establishment of a smaller and industrialised pastoral population while providing necessary education and career opportunities to the rest of the people in this area. The establishment of various industry sectors will be possible with the ranching system, while local livestock products will be able to compete with those from earlier adopters of the system in other provinces in China. The picture is appealing to external developers, yet the limitation of the land must be realised. Primary productivity may be the most distinctive limitation, especially in the Northern Tibetan plateau. The availability of water sources also limits the number of pastures and the output of livestock.

When dealing with disturbances, the ranching system may have a higher level of resistance, yet the options of adaptation are significantly reduced as mobility is largely lost. In this sense the resilience of the system is lower in the ranching system than in the nomadic system. However, looking at the problem at a higher perspective, one can say that converting to the ranching system in the context of changing climate and increasing population pressure creates adaptive options that were not available in the original system. The resilience for the pastoral system is reduced, but at the same time compensated by more possible means to develop in case pastoralism fails. At the same time the system's function to support biodiversity and human population can be preserved. Although there may be criticism about loss of traditional pastoralism, it must be recognised that the loss of social memory will likely cause such loss whether transformation to ranching takes place or not. Nomadic pastoralism has long been the core value of Tibetan society, yet in the face of complex challenges, sometimes it is necessary to abandon the core value in order to adapt to changed external world.

Although the transformation to ranching system may be necessary, current policy implementation may have some limitations. A sudden and uniform transformation may cause a heavy burden on local economy and aid. The central planning-style management may not be able to address differences in conditions and people's needs in the area. Most importantly, people accustomed to nomadic pastoralism still lack knowledge and skill preparation for a fully converted system, and cannot find enough job opportunities if they choose to leave the grassland. Only when implemented properly can ranching system enhance the adaptability and resilience of the system.

Appendix A

Model script and input file format

The model was constructed using functions implemented in three files. One of them, disturbance.R, generates random disturbances. The second file, readdata.R, read in data from input file. The third file, model.R, calculates the abundance of grass and shrub in time steps. All files were tested in R 2.7.1. The content of the three files are listed below:

disturbance.R:

```
library(evd)
dist <- function( idisturbance=disturbance,
lidisturbance=livestockdisturbance,
recrate=recoveryrate,
lrecrate=livestockrecoveryrate,
length=length,
probability=1,
disturb=disturb,
ldisturb=ldisturb )
  {
    disturb <- disturb * exp(recrate * (1-length))
```

```
    if(probability > rgev(1,loc=0.5,scale=0.5,shape=0.1))
# disturbance takes place
      {
        if(disturb >= 1e-06) { # disturbance seldom = 0
          recrate <- recrate * exp(-length)
          length <- length + 1
        }
        else {
          recrate <- recoveryrate
          length <- 1
        }
        disturb <- disturb + idisturbance
        # recoveryrate <- recrate
        # allow for existing disturbance to enhance each other
        # and slow down recovery
      }
    ldist2 <- ldist(idisturbance=idisturbance,
lidisturbance=lidisturbance,
lrecrate=lrecrate,
ldisturb=ldisturb,
disturb=disturb,
length=length)
    ldisturb <- ldist2$ldisturb
    lrecrate <- ldist2$lrecoveryrate
    if (disturb < 1e-06) {disturb <- 0}
    if (ldisturb < 1e-06) {ldisturb <- 0}
    list(disturb=disturb,
ldisturb=ldisturb,
recoveryrate=recrate,
```

```
lrecoveryrate=lrecrate ,
length=length )
  }

ldist <- function( idisturbance ,
lidisturbance , lrecrate ,
ldisturb , disturb , length  )
  # ratio is the value of livedisturbance:disturbance, used to
  # how severe the impact on livestock is, given a disturbance
  # vegetation.  Must be calculated before calling the function
  {
    ratio = lidisturbance / idisturbance
    if (disturb > 1e-06) {ldisturb <- disturb * ratio}
    else {
      ldisturb <- ldisturb * exp(lrecrate * (1-length))
    }
    list(ldisturb=ldisturb , lrecoveryrate=lrecrate)
  }
# idisturbance is somewhat related to that year's dist$disturb
# recovery rate can be considered a constant
```

readdata.R:

```
# Input data from given data file parameters.txt
parameter<-read.table(file="parameters.txt",sep="\␣",
col.names=c("attribute","value"))
grassquantity <- parameter$value[1]
shrubquantity <- parameter$value[2]
growthrategrass <- parameter$value[3]
growthrateshrub <- parameter$value[4]
grazingintensity <- parameter$value[5]
```

```
competitionshrubgrass <- parameter$value[6]
competitiongrassshrub <- parameter$value[7]
competitiongrassgrass <- parameter$value[8]
competitionshrubshrub <- parameter$value[9]
disturbance <- parameter$value[10]
livestockdisturbance <- parameter$value[11]
recoveryrate <- parameter$value[12]
livestockrecoveryrate <- parameter$value[13]
firerisk <- parameter$value[14]
years <- parameter$value[15]
distprobab <- parameter$value[16]
```

model.R:

```
source("readdata.R")
source("disturbance.R")
recrate <- recoveryrate
#recrate <- c(array(1,dim <- c(1,20)),
array(0.66,dim <- c(1,130)))
lrecrate <- livestockrecoveryrate
#lrecrate <- c(array(1.2,dim <- c(1,20)),
array(1,dim <- c(1,130)))
#distprobab <- c(array(0.3,dim <- c(1,20)),
array(0.2,dim <- c(1,130)))
disturb <- 0
ldisturb <- 0
g <- grassquantity
w <- shrubquantity
length <- 1
# How many consecutive year has the disturbance existed
grass <- array(0,dim <- years)
```

```
# storage of results
shrub <- array(0,dim <- years)
dg <- array(0,dim <- years)
dw <- array(0,dim <- years)
arrayd <- array(0,dim <- years)
# "array of disturbance"
arrayl <- array(0,dim <- years)
# "array of livestock disturbance"

    dgdt <- function( g=grassquantity,
w=shrubquantity,
dist,
ldist,
rg=growthrategrass,
s=grazingintensity,
cgg=competitiongrassgrass,
cwg=competitionshrubgrass,
cf=firerisk )
      {
        dgdt <- rg * g
* (1 - s * g / (g+w) * (1 - ldist)
- cgg * g - cwg * w - dist) - cf * g * g
      }
dwdt <- function( g=grassquantity,
w=shrubquantity,
rw=growthrateshrub,
cgw=competitiongrassshrub,
cww=competitionshrubshrub,
rg=growthrategrass,
```

```
s=grazingintensity ,
dist ,
ldist ,
cf=firerisk )
      {
        dwdt <- rw * w
* (1 - cgw * g - cww * w - s * w / (g+w)
* (1 - ldist) - 2 * dist) - g * cf * w
      }

for (i in seq(1:years)) {
  temp <- dist(idisturbance=disturbance ,
lidisturbance=livestockdisturbance ,
recrate=recrate ,
lrecrate=lrecrate ,
length=length ,
probability=distprobab ,
disturb=disturb ,
ldisturb=ldisturb)
#  temp <- dist(idisturbance=disturbance ,
lidisturbance=livestockdisturbance ,
recrate=recrate[i],
lrecrate=lrecrate[i],
length=length ,
probability=distprobab[i],
disturb=disturb ,
ldisturb=ldisturb)
  disturb <- temp$disturb
  recoveryrate <- temp$recoveryrate
```

```
  ldisturb <- temp$ldisturb
  livestockrecoveryrate <- temp$lrecoveryrate
  length=temp$length
  print(c(temp$recoveryrate,
temp$disturb,temp$lrecoveryrate,temp$ldisturb))
  arrayd[i] <- disturb
  arrayl[i] <- ldisturb
  dg[i] <- dgdt(g=g,w=w, dist=disturb,
ldist=ldisturb,rg=growthrategrass,
s=grazingintensity,cgg=competitiongrassgrass,
cwg=competitionshrubgrass)
  g <- dg[i] + g
  grass[i] <- g
  dw[i] <- dwdt(g=g,w=w, rw=growthrateshrub,
cgw=competitiongrassshrub,
cww=competitionshrubshrub,rg=growthrategrass,
s=grazingintensity,dist=disturb,
ldist=ldisturb,cf=firerisk)
  w <- dw[i] + w
  shrub[i] <- w
}
postscript(file="plot.eps",onefile=FALSE,
title="Simulation result",width=5,
height=5,horizontal=TRUE, paper="special",
colormodel="gray")
plot(shrub,grass,type="b",xlab="Shrub",ylab="Grass")
dev.off()
```

Spatialised model.R:

```
library(spgrass6)
```

```
cellnumber <- 22770
livestockdisturbance <- 1
period <- 150
length <- 1
### create disturbance base matrix
distmatrix <- array(0,dim <- c(cellnumber, 150))
### Functions about disturbances
source("disturbance.R")
# bring in dist() and ldist()
    dgdt <- function( g=grassquantity,
w=shrubquantity,
dist,
ldist,
rg=growthrategrass,
s=grazingintensity,
cgg=competitiongrassgrass,
cwg=competitionshrubgrass,
cf=firerisk )
      {
        dgdt <- rg * g
* (1 - s * (1 - ldist)
- cgg * g - cwg * w - dist) - cf * g * g
      }
    dwdt <- function( g=grassquantity,
w=shrubquantity,
rw=growthrateshrub,
cgw=competitiongrassshrub,
cww=competitionshrubshrub,
rg=growthrategrass,
```

```
s=grazingintensity ,
dist ,
ldist ,
cf=firerisk )
      {
        dwdt <- rw * w
* (1 - cgw * g - cww * w - 2 * dist)
- g * cf * w
      }
disturbance <- array(0,dim <- cellnumber)
disturbpara <- array(0,dim <- c(cellnumber ,2))
recoveryrate <- array(0,dim <- cellnumber)
livestockrecoveryrate <- array(0,dim <- cellnumber)

disturbpara[ ,1] <- data.frame(
readRAST6("disturbfrequency"))[ ,1]
disturbpara[ ,2] <- data.frame(
readRAST6("disturbintensity"))[ ,1]
recoveryrate <- data.frame(
readRAST6("vegrecovery"))[ ,1]
livestockrecoveryrate <- data.frame(
readRAST6("livrecovery"))[ ,1]
### data needed by dg and dw
g <- data.frame(readRAST6("grassabundance"))[ ,1]
w <- data.frame(readRAST6("shrubabundance"))[ ,1]
cwg <- data.frame(readRAST6("cwg"))[ ,1]
cgg <- data.frame(readRAST6("cgg"))[ ,1]
cgw <- data.frame(readRAST6("cgw"))[ ,1]
cww <- data.frame(readRAST6("cww"))[ ,1]
```

```
#grazingintensity <- data.frame(
readRAST6("grazingintensity"))[,1]
+ data.frame(readRAST6("settlementnomad"))[,1]
# grazing intensity considering nomadic setting
grazingintensity <- data.frame(
readRAST6("grazingintensity"))[,1]
+ data.frame(readRAST6("settlementurban"))[,1]
# grazing intensity considering ranch setting
firerisk <- 0
growthrategrass <- data.frame(
readRAST6("grategrass"))[,1]
+ rnorm(cellnumber, mean=0,sd=0.003)
growthrateshrub <- data.frame(
readRAST6("grateshrub"))[,1]
+ rnorm(cellnumber, mean=0,sd=0.003)
dw <- array(0,dim <- cellnumber)
dg <- array(0,dim <- cellnumber)
for (years in seq(1:period)) {
# changed the number so I can start from there
  for (pixels in seq(1:cellnumber)) {
    temp <- dist(
idisturbance=disturbpara[pixels,2],
lidisturbance=livestockdisturbance,
recrate=recoveryrate[pixels],
lrecrate=livestockrecoveryrate[pixels],
length=length,
probability=disturbpara[pixels,1],
disturb=disturbance[pixels],
ldisturb=livestockdisturbance)
```

```
    disturbance[pixels] <- temp$disturb
    recoveryrate[pixels] <- temp$recoveryrate
    livestockdisturbance <- temp$ldisturb
    livestockrecoveryrate[pixels] <- temp$lrecoveryrate
    length <- temp$length
    dg[pixels] <- dgdt(
g=g,w=w,dist=disturbance[pixels],
ldist=livestockdisturbance,rg=growthrategrass,
s=grazingintensity[pixels],cgg=cgg,cwg=cwg)
    dw[pixels] <- dwdt(
g=g,w=w,rw=growthrateshrub,
cgw=cgw,cww=cww,rg=growthrategrass,
s=grazingintensity[pixels],dist=disturbance[pixels],
ldist=livestockdisturbance,cf=firerisk)
    g[pixels] <- dg[pixels] + g[pixels]
    w[pixels] <- dw[pixels] + w[pixels]
  }
  map <- readRAST6("ndvizscore30",NODATA=0)
  map[["ndvizscore30"]] <- g
  message(
paste("Generating␣grass␣map",years,"...",sep="␣"))
  writeRAST6(
x=map,vname=paste("USIMULATIONgrass",years,sep=""),
zcol=1,NODATA=-9999)
# output of simulated map
  message("...␣done.")
  map[["ndvizscore30"]] <- w
  message(
paste("Generating␣shrub␣map",years,"...",sep="␣"))
```

```
  writeRAST6(x=map, vname=paste("USIMULATIONshrub",
years, sep=""),
zcol=1,NODATA=-9999)
  message("... done.")
  growthrategrass <- data.frame(
readRAST6("grategrass"))[,1]
+ rnorm(cellnumber, mean=0,sd=0.003)
  growthrateshrub <- data.frame(
readRAST6("grateshrub"))[,1]
+ rnorm(cellnumber, mean=0,sd=0.003)
# regenerate randomised growth rate
}
```

An example input file is listed below:

```
g:grass_quantity 1
w:shrub_quantity 1
r_{g}:growth_rate_grass 0.09
r_{w}:growth_rate_shrub 0.11
s:grazing_intensity 0.38
c_{wg}:competition 0.16
c_{gw}:competition 0.16
c_{gg}:competition 0.3
c_{ww}:competition 0.3
e_{g,w}:disturbance 0.1
e_{l}:livestockdisturbance 0.1
c_{e}:recovery_rate 0.66
cl_{e}:livestockrecovery_rate 1
c_{f}:fire_risk 0
years 150
distprobab 0.2
```

Appendix B

Conceptual model visualisation

>

The Graphviz script used to visualise the conceptual model is as below.

```
digraph conceptmodel {
  size="7.5,10"
  ratio=auto
      graph [sep="+1",overlap=scale,outputorder=nodesfirst,
             splines=true]
      /* fast changing ones */
      {node [shape=circle,style=filled,color=skyblue,
       fontname=Helvetica,fontsize=45];
              snowstorm [label="Snowstorm"];
              livestock [label="Livestock"];
              drought [label="Drought"];
              fire [label="Fire"];
              erosion [label="Soil␣Erosion"];
      }
      /* slowly changing ones */
```

```
{node [shape=circle ,style=filled ,color=yellow ,
 fontname=Helvetica ,fontsize =45];
        seedbank [label="Seed\␣bank"];
        biodiversity [label="Biodiversity"];
        climate [label="Climate␣change"];
        population [label="Population"];
        socialeffect [label="Social\n␣effectiveness"];
        socialfair [label="Social␣fairness"];
        altitude [label="Altitude"];
        slope [label="Slope"];
}
/* cross-scale ones */
{node [shape=box,style=filled ,color=lawngreen ,
 fontname=Helvetica ,fontsize =45];
        temperature [label="Temperature"];
        precipitation [label="Precipitation"];
        soilnutrient [label="Soil␣nutrient"];
        soilmoisture [label="Soil␣moisture"];
        wateravailable [label="Water␣availability"];
        wildlife [label="Wildlife"];
        grass [label="Grass␣availability"];
        settlement [label="Settlements"];
        economic [label="Economic␣\nviability"];
        demand [label="Market␣demand"];
        mobility [label="Mobility"];
}
/* interactions */
/* within-scale ones*/
{edge [fontsize=20,fontname=Helvetica ,
```

```
labelfontsize=30,arrowsize=3.0];
        snowstorm -> livestock [arrowhead="empty"];
        drought -> livestock [arrowhead="empty"];
        snowstorm -> soilmoisture [arrowhead="normal"];
        snowstorm -> wildlife [arrowhead="empty"];
        livestock -> seedbank [arrowhead="normal"];
        snowstorm -> seedbank [arrowhead="empty"];
        drought -> soilmoisture [arrowhead="empty"];
        drought -> wateravailable [arrowhead="empty"];
        population -> demand [arrowhead="normal"];
        altitude -> temperature [arrowhead="empty"];
        altitude -> wateravailable [arrowhead="empty"];
        altitude -> population [arrowhead="empty"];
        slope -> wateravailable [arrowhead="empty"];
        slope -> population [arrowhead="empty"];
        temperature -> grass [arrowhead="ediamond"];
        precipitation -> soilmoisture
         [arrowhead="normal"];
        soilnutrient -> grass [arrowhead="normal"];
        soilmoisture -> grass [arrowhead="normal"];
        grass -> livestock [arrowhead="normal",
    arrowtail="empty",dir=both];
        settlement -> population [arrowtail="normal",
        arrowhead="normal",dir=both];
        livestock -> erosion [arrowhead="normal"];
        erosion -> grass [arrowhead="empty"];
        precipitation -> erosion [arrowhead="normal"];
        fire -> erosion [arrowhead="normal"];
        slope -> erosion [arrowhead="normal"];
```

```
}
/* cross-scale ones */
{edge [fontsize=20,fontname=Helvetica ,color=blue ,
 labelfontsize=30,arrowsize=3.0];
        snowstorm -> grass [arrowhead="empty"];
        livestock -> biodiversity
      [arrowhead="ediamond"];
        livestock -> soilnutrient [arrowhead="normal"];
        livestock -> wildlife
      [dir=both ,arrowhead="empty",
      arrowtail="empty"];
        livestock -> settlement [arrowhead="normal"];
        livestock -> economic [arrowhead="normal"];
        drought -> grass [arrowhead="empty"];
        drought -> fire [arrowhead="normal"];
        fire -> seedbank [arrowhead="empty"];
        fire -> soilnutrient [arrowhead="empty"];
        seedbank -> grass [arrowtail="normal",
     dir=both ,arrowhead="normal"];
        biodiversity -> grass [arrowhead="normal"];
        biodiversity -> wildlife
    [dir=both ,arrowhead="normal",
    arrowtail="normal"];
        climate -> temperature [arrowhead="normal"];
        climate -> precipitation
      [arrowhead="empty"];
        population -> livestock
    [dir=both , arrowtail="normal",
    arrowhead="normal"];
```

```
        population -> biodiversity
    [arrowhead="empty"];
        population -> socialeffect
    [arrowhead="empty"];
        population -> wateravailable
      [arrowhead="empty",
      arrowtail="normal",
      dir=both];
        population -> grass [arrowhead="empty"];
        population -> economic [arrowhead="normal"];
        population -> mobility [arrowhead="empty"];
        socialfair -> economic [arrowhead="normal"];
        socialfair -> demand [arrowhead="normal"];
        socialeffect -> economic [arrowhead="normal"];
        temperature -> drought [arrowhead="normal"];
        precipitation -> grass [arrowhead="normal"];
        precipitation -> wateravailable
     [arrowhead="normal"];
        wateravailable -> grass [arrowhead="normal"];
        wateravailable -> wildlife
         [arrowhead="normal"];
        wateravailable -> livestock
         [arrowhead="normal"];
        economic -> demand [arrowhead="normal"];
        settlement -> mobility [arrowhead="empty"];
        mobility -> livestock [arrowhead="normal"];
        mobility -> grass [arrowhead="normal"];
  }
}
```

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