# Pedogenesis of Alpine Meadow Soils in the Eastern Qinghai-Tibet Plateau, China

January 2021

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A Dissertation Submitted to
the Graduate School of Life and Environmental Sciences,
the University of Tsukuba
in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy in Agricultural Science

(Doctoral Program in Biosphere Resource Science and Technology)

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**Summary**

The Qinghai-Tibet plateau (QTP) covering an area of nearly 2.58 million $km^2$ with elevation ranging from 3000 to 5000 m. Thus, it is often referred to as the "third pole" or "the roof of the world." The QTP is one of the most famous grazing ecosystems and among the largest grassland ecosystem in the world. The QTP pasture is dominated by typical alpine grass "*Kobresia"*. *Kobresia* covers an area of 450,000 $km^2$ extending from the north-eastern plateau to the north slope of Mount Everest (3000 m-6000 m a.s.l.) in the world. A unique soil surface structure called "mattic epipedon" (Chinese Soil Taxnomy) has emerged here. The mattic epipedon is characterized by enriched in rhizogenic organic matter, and the intertwining of living and dead root systems to form extremely firm turf, felt-like surface layer that ranges in thickness from 1 to 30 cm, which protects large surfaces against erosion. In recent years, the QTP is currently suffering from severe ecological problems, extensive soil degradation has occurred as a result of the destruction of the mattic epipedon. However, the mattic epipedon as a soil horizon in pedology, there is limited research on the structure property of the mattic epipedon. In this study, I aim to reveal the pedogenic of the mattic epipedon in alpine meadow and its response mechanism to grassland degradation.

Firstly, in order to investigate the geographical distribution of the mattic epipedon, three sites were selected according to the altitude gradient: Laneika (L-L, 3200m a.s.l.), Gongba (G-C, 3480m a.s.l.) and Langmu (L-H, 3820m a.s.l.). In addition, a sample plot was selected from Gongba in order to better interpret the soil formation process of the mattic epipedon, which is characterized by the fact that the original layer was destroyed and a new mattic epipedon begins to form. The soils observed in L-L were classified as Luvic Phaeozems, the G-C, G-N and L-H soils were Calcaric Phaeozems. The results showed mattic epipedon is predominantly distributed at area of altitude with 3480 m and 3820 m, dense root mat occurred at site of 3480 m. The root morphology shown the intense root-mat structure existed in G-C and G-N, root biomass also was higher in G-C (11.04 kg $m^{-2}$) and G-N (4.47 kg $m^{-2}$). The G-C with complete mattic epipedon has the highest

hardness, OM content, soil porosity, and soil critter activity because of its intense root mixture system. The soil micromorphology showed that the mattic horizon holds a larger pore area than the A1 horizon, and G-C had a highest organic component of 77%, followed by G-N with 55%, L-H with 52% and L-L was the lowest only 25%. And I use soil micromorphological techniques to determine the origin and degree of decomposition of OM in the mattic epipedon. The results showed that litter decomposition will increase with increasing temperature, the highest degree of decomposition arise in L-L.

Secondly, I focus on the response of the mattic epipedon to soil degradation, three sites where different degradation were chosen from the Hequ horse farm: lightly degraded meadow (HQ1-L); moderately degraded meadow (HQ2-M); and heavily degraded meadow (HQ3-H), according to the investigation of plant and land use. The results showed that the soil of the farms respectively classify as Luvic Phaeozems (HQ1-L), Haplic Phaeozems (HQ2-M), and Calcaric Phaeozems (HQ3-H). A vegetation survey and soil profile morphology showed that *Kobresia* was the dominant species in HQ1-L and HQ2-M, featuring in topsoil horizons rich in rhizogenic organic matter which creates turfs. The results showed that, the presence of the mattic epipedon had influenced changes in soil physicochemical properties such that exchangeable cations, cation exchangeable capacity, total nitrogen, and organic carbon decrease during the degradation of grassland; however, the pH value showed an opposite trend. Further results on soil micromorphological features revealed that, with increased intensity of soil degradation, soil porosity and fractal dimension tend to decrease, and the soil microstructure evolves to an intergrain micro-aggregate structure. Also, by counting the number of excrements in the soil thin sections, and combining this with the fractal dimension of the porosity, I found the HQ1-L was more conducive to soil fauna survival, when compared with HQ2-M, and HQ3-H.

Finally, the results of my study as a whole show that the mattic epipedon plays a crucial role in soil degradation, the geographic distribution of the mattic epipedon is characterized by factors such as vegetation cover, altitude, slope and orientation. The recovery from damage of the mattic epipedon is possible, however, that restoration to its original state takes least 60 years, and furthermore, secondary damage (overgrazing and rodent activity) caused by other factors must be strictly controlled. This process that impedes local livestock production as well as causing incalculable damage to the ecology of the QTP. Therefore, a series of conservation actions must be implemented from the appearance of damage signals in the mattic epipedon (Such as stage of HQ2-M, including reduction of livestock numbers, seasonal nomadic grazing activities and control of rodent populations, the more advocated method is by increasing the number of small rodent predators). It is important to protect the integrity of the mattic epipedon, and to prevent grassland degradation as the main task.

**Content**

**Chapter 1** ........ **1**

**General Introduction** ........ **1**

**1.1 Background of Research** ........ **1**

**1.1.1 Basic overview of the Qinghai-Tibet Plateau** ........ 1

**1.1.2 The Kobresia pasture in the QTP** ........ 2

**1.1.3 "Mattic epipedon" a special soil surface horizon** ........ 2

**1.1.4 Pedogenesis Characteristic and Main Soil Types of Alpine Meadow** ........ 4

**1.1.5 Current ecological problems of the QTP** ........ 5

**1.2 The purpose of research** ........ **7**

**Chapter 2** ........ **8**

**Structural characteristics of the soil top-horizon at different altitudes and the restoration of the mattic epipedon** ........ **8**

**Summary** ........ **8**

**Chapter 3** ........ **9**

**Physicochemical Properties and Micromorphology of Degraded Alpine Meadow Soils** ........ **9**

**3.1 Introduction** ........ **9**

**3.2 Materials and methods** ........ **11**

**3.2.1 Study sites** ........ 11

**3.2.2 Identification of vegetation types and intensity in the studied degraded farms** ........ 12

**3.2.3 Determination of soil properties** ........ 13

**3.2.3.1 Analysis of soil physicochemical properties** ........ 13

**3.2.3.2 Preparation and description of soil thin sections**................................ 14

**3.2.3.3 Quantifying porosity and measurement of fractal dimensions** .......... 14

**3.3 Results**........................................................................................................ **15**

**3.3.1 Vegetations in the studied farms with varying degrees of soil degradation**
......................................................................................................................... 15

**3.3.2 Morphological properties of the studied soils with varying degrees of degradation** ....................................................................................................... 15

**3.3.3 Chemical characteristics of studied soils with varying degrees of degradation** ....................................................................................................... 16

**3.3.4 Soils of the studied farms with varying degrees of soil degradation**......... 17

**3.3.5 Micromorphological characteristics of the top horizon**............................ 18

**3.3.6 Fractal dimensions of soil microstructure**.................................................. 18

**3.4 Discussions**.................................................................................................. **19**

**3.4.1 Soil properties and vegetation with meadow degradation degree** ............ 19

**3.4.2 The micromorphological characteristics with meadow degradation degree**
......................................................................................................................... 21

**3.5 Conclusion** .................................................................................................. **22**

**Chapter 4** ......................................................................................................... **35**

**General Discussion** ......................................................................................... **35**

**4.1 Pedogenesis of Alpine Meadow** .................................................................. **35**

**4.2 Distribution Characteristics of Mattic Epipedon** ........................................ **36**

**4.3 Formation Processes of Mattic Epipedon**.................................................... **37**

**4.4 Conservation of mattic epipedon** ................................................................ **39**

**Acknowledgements**.......................................................................................... **42**

**Reference** ......................................................................................................... **43**

## List of Tables

**Table 3- 1 Major species of the study sites. Showing the SDR2 value and Shannon-Wiener's index. .................................................................... 24**

**Table 3- 2 Brief description of the soil profile morphology. ................................ 25**

**Table 3- 3 Chemical characteristics of the studied soil profiles .......................... 26**

**Table 3- 4 Extractable Fe, Al, Si and Ca ............................................................... 27**

**Table 3- 5 Characteristics of the soil micromorphological .................................. 28**

## List of Figures

**Figure 3- 1 Location of study sites in Maqu within QTP........................................29**

**Figure 3- 2 Photographs of the profiles investigated.............................................30**

**Figure 3- 3 Microstructure of top horizon .............................................................31**

**Figure 3- 4 Photomicrographs from the top horizon ............................................32**

**Figure 3- 5 Fractal analysis of the top horizon of HQ1-L, HQ2-M and HQ3-H33**

**Figure 3- 6 Measurement porosity by image J .......................................................34**

**Figure 4- 1 Pedogenesis Processes of Mattic Epipedon.........................................41**

# Chapter 1

# General Introduction

## 1.1 Background of Research

### 1.1.1 Basic overview of the Qinghai-Tibet Plateau

The Qinghai-Tibet plateau (QTP), which is the highest plateau in the world, covers nearly 2.5 million $km^2$, accounting for approximately 30% of the world's plateaus above 3,000 meters in altitude, thus, it is often referred to as the “third pole” or “the roof of the world.” The QTP is between latitude 26°00′ to 39 °47′N and longitude 73°19′ to 104°47′E, with an east to west length of about 3000 km and a north to south width of about 1500 km (Li et al., 2013b). Following the Antarctic and Arctic, the QTP constitutes the largest reservoir of snow and ice on Earth (Qiu, 2008). This area also called the “water tower of China”, because here are the headwaters of many major rivers, including the Yellow River, the Yangtze, the Lancang and the Brahmaputra etc. Also, the QTP is one of the world's important hotspots of alpine biodiversity, with between 9,000 and 12,000 plant species distributed along altitudinal gradients (Liu et al., 2014).

Due to the special longitudinal and latitudinal distribution and mountainous vertical climate zones on the QTP, a variety plateau ecosystem has been formed, including grassland ecosystems, desert ecosystems, forest ecosystems, wetland ecosystems and farmland ecosystems (Niu, 1999). Grassland ecosystems are the most widely distributed on the QTP, accounting for more than half of the plateau area (Chen et al., 2014). Thus the QTP is one of the world’s major pastoral areas, where consist mainly of alpine steppe (49.3%), alpine meadow (44.9%) and alpine desert (5.9%) (Long et al., 2003). Due to the limited area under cultivation and the harsh natural environment of the Tibetan Plateau, livestock grazing has become the dominant land use and the main economic component of the region. The yak (*Bos grunniens*) and Tibetan sheep (*Ovis aries*) are the dominant livestock on the QTP (Wiener et al., 2011).

### 1.1.2 The *Kobresia* pasture in the QTP

On the QTP is a unique ecosystem known as *Kobresia* pasture, which extends from 3,000 meters a.s.l. in the northeast to 6,000 meters a.s.l. in the south, covering an area of 450,000 $km^2$ (Miehe et al., 2008). Some previous studies have reported that such *Kobresia* pastures originated in the late Holocene approximately 2,000 years ago as a result of anthropogenic (grazing) influences, which established a type of vegetation more adapted to modern grazing systems (Kaiser et al., 2008; Schlutz and Lehmkuhl, 2009). Because of its cold-hardiness of *Kobresia*, there are up to 36 species of *Kobresia* genus distributed on the QTP, including five endemic species (Zhang et al., 1995).

*Kobresia* is a perennial herb with well-developed below-ground rhizomes, it mainly relies on germinate of rhizomes to reproduce, thus in the short summer of the QTP, it can reproduce as usual without seed maturity, and the live roots are protected by a large number of dead roots to withstand the harsh winter. And the leaves of the *Kobresia* have a thick cuticle with the margins rolled up toward the abdomen to form needles， which are adapted to the harsh climatic conditions of low temperatures, high winds and strong radiation at high altitudes(Wu et al., 2010b; Zhang et al., 1995). The most dominant of these genera include *K. pygmaea, K. microglochin, K. humilis, K. bellardii, K. capillifolia, K. royleana, K. tibetica, K. K. setchwanensis, K. kansuensis* (Qiao and Duan, 2016).

### 1.1.3 “Mattic epipedon” a special soil surface horizon

Mattic epipedon is special diagnostic surface horizons for pedological in Chinese Soil Taxonomy, it is characterized by enriched in rhizogenic organic matter and the intertwining of living and dead root systems to form a felt-like soil surface. It has the following conditions (Gong and Chen, 1999);

(1) thicker than 5 cm, elastic and difficult to dig with a shovel;

(2) mixed root structure volume is more than half of the total volume;

(3) the hue is between 7.5 YR and 10 YR because of varying degrees of internal decomposition;

(4) the Carbon to Nitrogen ratio generally ranges between 14 and 20;

(5) water saturation time is generally less than one month;

(6) the soil's bulk density range between 0.5 to 1.1 Mg $m^{-3}$;

(7) have a low soil temperature.

The naming of the turf horizon has not been completely unified, because of it felt-like surface, it is also commonly known as turfs, sods, mats or swards, Kaiser, (2004) named it Afe horizon, with the suffix “fe” being an abbreviation of “felty”. In this study, I term it “OA” horizon based on conventional pedological because of the large number of organic roots mixed in its topsoil. Also because of its color, rich SOM content and high base saturation (＞50%), I classify it in the category of mollic horizon, but it should be distinguished from mollic A horizon because of its crumb structure and hard texture(Kaiser et al., 2008; WRB and IUSS, 2015).

*Kobresia* provides the material basis for root-mat because of its dense root system. Secondly, the *Kobresia*-dominated pastures are distributed in high altitude areas(3000 m-6000 m a.s.l.) with cold and seasonally dry environment, dead roots are not fully decomposed and mixed with new roots, and in order to provide nutrients for plant growth, the mattic epipedon will gradually become thicker(Kaiser et al., 2008; Miehe et al., 2008; Schleuss et al., 2015). The mattic epipedon due to its physical characteristics, such as its dense root network structure and hard texture, provides a buffer against trampling by livestock and largely resists burrowing behavior by rodents (Miehe et al., 2008). The mattic epipedon is the most active layer of biological nutrient cycling in the alpine meadow, due to characterized by high contents of moisture, porosity, organic carbon (OC), total nitrogen (TN) and cation exchangeable capacity (CEC) and moderate pH value(Baumann et al., 2009; Miehe et al., 2019), In some studies, there were storage of as much as 15.2 kg C $m^{-2}$

of organic carbon in the turf (Schleuss et al., 2015; Unteregelsbacher et al., 2012). The mattic epipedon is an important protective cover of alpine meadows on the QTP.

The current destruction of the mattic epipedon is extremely serious (Shang and Long, 2007). In the local area, because of its hard texture, the mattic epipedon is often removed completely and used for building walls. Moreover, due to road construction, sand mining and other activities, the mattic epipedon is extensively destroyed, and this kind of destruction is irreversible. In my field studies desertification is occurring around the destroyed mattic epipedon. Many studies have found that the destruction of the mattic epipedon leads to the formation of a phenomenon called "black beach"(Dong et al., 2013; Ma and Wang, 1999; Shang and Long, 2007), the soil surface horizon is completely destroyed due to overgrazing and rodent interaction, and thus the black subsoil is exposed. The ecological environment of the QTP is worsening due to the expansion of "black beach" degraded grasslands.

### 1.1.4 Pedogenesis Characteristic and Main Soil Types of Alpine Meadow

Alpine meadows are mainly found in the alpine zone or the cold temperate zone of the mountains in the QTP, where the cold climate is the dominant soil forming factor, it is characterized by long dry and cold seasons( range from Oct. to May ), short warm and wet seasons (range from Jun to Sep.), and long periods of soil freezing with average annual temperature of -6 to 4 ℃, frequent freeze-thaw cycles, and the annul precipitation of 300 to 700 mm(Gong and Chen, 1999). Secondly, the vegetation type is closely related to the soil formation, mainly by the perennial Cyperaceae (genus *Kobresia*) (Miehe et al., 2019). *Kobresia* produces a root mat that is used as a diagnostic horizon (mattic epipedon). The soil parent material consists mainly of conglomerate, granite, and red mudstone in the form of residual sediment, slope deposits, and glacial till and glaciofluvial deposit(Chen et al., 2019), Soils are characterized by young development and weak soil weathering, and the predominant soil types are Leptosols, Kastanozems, Phaeozems, Regosols, Umbrisols, Cambisols and Calcisols, which covered by mattic epipedon (Baumann et al., 2009; Miehe et al., 2019).

### 1.1.5 Current ecological problems of the QTP

Qiu, (2008) reports that temperatures on the Tibetan Plateau have continued to rise by 1.5°C over the past 50 years, which is three times faster than the rate of global warming. Due to the QTP has the largest extent of permafrost in the low to middle latitudes of the world, where become one of the regions most affected by global climate change and direct contribution to the atmospheric greenhouse gas content (Wu et al., 2010a). The ecosystems of the QTP are more sensitive and vulnerable to global climate change, coupled with the threat of human activities, has led to a series of problems in the QTP ecosystem in recent decades, including glacial retreat, permafrost melting, reduced river flows, shrinking lakes and wetlands, grassland degradation, accelerated desertification, threats to biodiversity (Brierley et al., 2016).

Currently, grassland degradation is the most serious problem in the QTP, the degraded area amount to $4.251x10^7$ ha, which is one third of the available area(Shang and Long, 2007), there are many factors that contribute to grassland degradation, including climate change, human activities, and rodent destruction, and it is important to emphasize that their combination and interaction can exacerbate the occurrence of degradation. Human activities mainly refer to overgrazing and construction (mining, road construction, sand excavation and the damming of a river for a hydropower station) due to rising population. The ecological damage caused by construction is now well ameliorated by strict policy controls. There is evidence that overgrazing can severely disrupt community structure and result in reduced regenerative ability of grassland vegetation (Su et al., 2004). Prolonged grazing and overgrazing reduce the accumulation of plant litter in the soil, thereby affecting microbial activity and reducing soil fertility (Shang and Long, 2007). Zhang et al. (2014) reports that overgrazing has been widespread across the QTP in recent decades, with overgrazing rates ranging from 27% to 89%.

The QTP is also the habitat of many rodents, mainly plateau pika (*Ochotona curzoniae*) and marmots (*Marmota himalayana*), whose burrowing and gnawing behaviors break through thematic epipedon and expose the subsoil (Li et al., 2016; Zhou et al., 2005). The ecological impact of the burrowing behavior of these rodents (pika) on the QTP has been controversial. Some scholars argue that they are a keystone species on the QTP whose burrowing behavior not only recycles soil but also provides shelter for other small animals, and increasing the infiltration rate of water (Davidson et al., 2012; Delibes-Mateos et al., 2011; Lai and Smith, 2003; Smith and Foggin, 1999; Wilson and Smith, 2014). There is no doubt that pikas are a keystone species for biodiversity, but their overabundance can accelerate soil erosion. Ma et al. (1998) reported that in some regions their numbers reached as far as 374 pikas $ha^{-1}$, this leads to burrow densities of up to 2000 $ha^{-1}$ (Pech et al., 2007). Overgrazing often coincides with rodent outbreaks, and the decline in vegetation cover caused by overgrazing can lead to a population explosion of pika (Harris, 2010; Li et al., 2013b). Li et al. (2016) reported that rodents (pikas, etc.) are likely to exacerbate rather than cause pasture degradation, and reasonable control of rodent populations will have a positive effect on soil fertility and microbial viability.

The organic carbon of $3.84 \times 10^9$ t was stored in soil at 0-72 cm depth on the QTP (Zhao et al., 2018), approximately 33.5 Pg C of soil organic carbon was stored in grasslands, with 37% stored in permafrost areas (Wang et al., 2002). The QTP is one of the most sensitive regions to global warming, especially permafrost area (Wang et al., 2006). The global warming will promote the net loss of soil carbon to the atmosphere, meanwhile, driving a positive land carbon-climate feedback that could accelerate climatic change (Crowther et al., 2016). There are reports indicating SOC losses due to degradation of up to 1.8 Tg C in the permafrost zone above 30 cm of soil surface during period of 1986 to 2000. The degradation of the alpine grasslands is expected to become more severe under the global warming trend, therefore, it is important to pay more attention to the fragile ecosystem of the QTP.

## 1.2 The purpose of research

From the above, the degradation of the alpine grasslands due to climate change and human factors is becoming increasingly severe, posing a serious threat to the ecological environment of the QTP. The mattic epipedon is a powerful “armor” that plays a crucial role in the protection of alpine grasslands, and current research on the mattic epipedon is mainly focused on its origin, vegetation composition, and some functional studies(Kaiser et al., 2008; Miehe et al., 2008; Miehe et al., 2019; Unteregelsbacher et al., 2012; Yang et al., 2016; Zhi et al., 2017). However, the mattic epipedon as a soil horizon in pedology, there is limited research on the specific structure of the mattic epipedon. Therefore, in this study, I aim to reveal the pedogenesis of the mattic epipedon in alpine meadow and its response mechanism to grassland degradation.

In the chapter 2, the distribution characteristics of the mattic epipedon under altitude gradient was investigated, and the soil micromorphological techniques was used to determining the origin and degree of decomposition of OM in the top horizon under different altitude. In chapter 3, I will focus on the clarify the morphological characteristics and physicochemical properties of soils under different degraded meadow, and the soil micromorphological of top horizon was investigated. Furthermore, in chapter 4, I discussed the process of pedogenic and the possibility of rebuilding the mattic epipedon after its destruction. The shortcomings of this study were summarized, and a future perspective on this subject was presented.

## Chapter 2

## Structural characteristics of the soil top-horizon at different altitudes and the restoration of the mattic epipedon


### Summary

In this chapter, in order to investigate the geographical distribution of the mattic epipedon, three sites were selected according to the altitude gradient: Laneika (L-L, 3200m a.s.l.), Gongba (G-C, 3480m a.s.l.) and Langmu (L-H, 3820m a.s.l.). In addition, a sample plot was selected from Gongba in order to better interpret the soil formation process of the mattic epipedon, which is characterized by the fact that the original layer was destroyed and a new mattic epipedon begins to form. The soils observed in L-L were classified as Luvic Phaeozems, the G-C, G-N and L-H soils were Calcaric Phaeozems. The results showed mattic epipedon is predominantly distributed at area of altitude with 3480 m and 3820 m, dense root mat occurred at site of 3480 m. The root morphology shown the intense root-mat structure existed in G-C and G-N, root biomass also was higher in G-C (11.04 kg $m^{-2}$) and G-N (4.47 kg $m^{-2}$). The G-C with complete mattic epipedon has the highest hardness, OM content, soil porosity, and soil critter activity because of its intense root mixture system. The soil micromorphology showed that the mattic horizon holds a larger pore area than the A1 horizon, and G-C had a highest organic component of 77%, followed by G-N with 55%, L-H with 52% and L-L was the lowest only 25%. And I use soil micromorphological techniques to determine the origin and degree of decomposition of OM in the mattic epipedon. The results showed that litter decomposition will increase with increasing temperature, the highest degree of decomposition arise in L-L.

## Chapter 3

## Physicochemical Properties and Micromorphology of Degraded Alpine Meadow Soils

### 3.1 Introduction

The Qinghai-Tibet plateau (QTP) is a vast elevated plateau in Central Asia and East Asia; its precise position is between latitude 26 °00′ to 39 °47′ N and longitude 73 °19′ to 104 °47′ E (Fig. 3-1). It is the single largest and highest plateau in the world, covering an area of nearly 2.58 million km$^2$ with elevation ranging from 3,000 to 5,000 m. Thus, it is often referred to as the "third pole" or "the roof of the world." The QTP is one of the most famous grazing ecosystems and among the largest grassland systems in the world. The QTP pasture is dominated by special alpine grass "*Kobresia*". *Kobresia* covers an area of 450,000 km$^2$ extending from the north-eastern plateau to the north slope of Mount Everest (3000 m-6000 m a.s.l.) in the world (Miehe et al., 2019). *Kobresia* forms a very compact felty root mat at soil surface and makes unique ecosystems (Miehe et al., 2008).

The principal ecological characteristic of *Kobresia* (Cyperaceae) is a very developed root system, resulting in intensively root-mixed topsoils horizons in the alpine meadow areas; this root-felty surface horizon is termed the "mattic epipedon" in Chinese Soil Taxonomy (also named *turfs*, mats and sods) that are between 1 and 30 cm thickness, and this mattic epipedon consists mainly of living and dead roots, humus and minerogenic matter (Kaiser et al., 2008; Miehe et al., 2011; Schleuss et al., 2015). With a large water storage capacity, it is the most active horizon of biological nutrient cycling in the alpine meadow and contains high soil organic carbon (SOC) contents (Baumann et al., 2009; Yang et al., 2016). *Kobresia* pasture is reported as an important part of carbon storage in the world which the 21.7 Pg of C stored in the 0-0.75m profile of soil (Wang et al., 2002). The mattic epipedon has an intensive root network that protect soils against trampling by livestock, in addition its massive underground biomass absorbs and stores large amount of nutrients to support rapid regrowth after grazing (Miehe et al., 2011; Schmitt et al., 2013;

Sun et al., 2018). Therefore, as the surface layer of soil, the mattic epipedon plays a critical role due to its unique structure and hard texture in soil and water conservation and its ecological protection. However, due to the QTP ecosystem displays characteristics of harsh environmental conditions, such as low temperatures, water shortages and high solar radiation, that lead to low soil nutrition and reproductive activities and poor grassland vegetation renewal rates (Cui et al., 2007). The vulnerability of the alpine ecosystem of the QTP means that it would be very difficult to rehabilitate once destroyed (Wiener et al., 2011).

Both natural and human factors have caused the degradation of the grassland area to approximately $4.251 \times 10^7$ $hm^2$, accounting for 33% of the available grassland area (Shang and Long, 2007). This significant grassland degradation threatens the ecological environment of the plateau. Natural factors include warming and drying of the climate, an increase in the populations of native small mammals such as plateau pikas (*Ochotona curzoniae*), wind and water erosion, and freeze-thaw stripping of the sod layer. Human factors including increased livestock numbers have led to seasonal overgrazing, mining, road construction, sand excavation and the damming of a river for a hydropower station (He et al., 2008). Especially, the effects on biodiversity of long-term overgrazing is serious (Milchunas et al., 1998; Arthur et al., 2008). The ecophysiological characteristics of plant species can be changed by grazing, and the relative abundance of plants will change (Niu et al., 2009). For example, Du et al. (2008) reported that Cyperaceae gradually replaced Gramineae as the dominant community with increasing of grazing intensity. The *Kobresia* pasture is degradable through livestock, and the black patches appeared in overgrazing region (Meihe et al., 2011; Zhang et al., 2017). Therefore, it is necessary to study the effect of overgrazing on mattic epipedon.

In the QTP, the grassland degradation is a complex process, the previous researches mostly focused on the plant composition and succession(Shang et al., 2008; Miehe et al., 2011; Li et al., 2014) and the change of soil element content (Ma et al., 2016; Liu et al., 2018; Yang et al., 2019). However, there has been no micromorphology characteristics investigation on the mattic epipedon so far. The soil micromorphological analysis is a useful method to assessment of soil quality (Bullock et al., 1985). By observing the microstructure, voids, organic composition and excrement pedofeatures of mattic epipedon in different degradation states, I can clarify the response mechanism of mattic epipedon to soil degradation and its effect on the protection of the ecological environment of the QTP. Therefore, in this study, I aimed to: (1) clarify the morphological characteristics and physicochemical properties of soils in alpine degraded meadow; and (2) investigate the change of soil micromorphology under different meadow degradation conditions.

## 3.2 Materials and methods

### 3.2.1 Study sites

This study was conducted at the Hequ horse farm (HQ). The Hequ horse farm is located in the southern part of Maqu County (Fig. 3-1), and was built in 1958 to become the center of the cultivation of Hequ horse. Due to long-term natural and artificial selection, the yak, Tibetan sheep, and Hequ horse have become the major livestock species able to adapt to the harsh local environment. Maqu County, on the border between Gansu and Sichuan provinces, China, is located between latitude 33 °30′ to 34 °15′ N and longitude 101 °38′ to 102 °45′ E, and its elevation ranges from 3,200 m to 4,200 m a.s.l. According to the Koeppen Classification System, it has a wet and cold climate, with dry winters and rainy summers due to the monsoon, and an annual average temperature of 1.88 °C (ranging from −10.78 °C in January to 11.78 °C in July). The growing season temperature maxima is 23.6–28.98 °C and there are 270 frost days annually. Over 90% of the precipitation is concentrated in the plant growing season, which lasts from June to September, and the mean annual precipitation is 594 mm, with the annual evaporation being 1,202 mm, and the average relative humidity being 62% (Cao et al., 2011; Cao et al., 2012; Dente et al., 2012). With abundant natural grassland resources, Maqu County is the important stockbreeding base in the upper reaches of the Yellow River.

In this study, according to the investigation of plant and land use, I chose three study sites. The first of these, lightly degraded meadow (HQ1-L) was located at 33 °54′ 54′′ N and 102° 08′ 19′′ E, and an altitude of 3,430 m (Fig. 3-1). According to the local herdsmen, the livestock are transferred to this area only for winter pasture grazing. Moderately degraded meadow (HQ2-M) was located at 33 °55′ 17′′ N and 102 °09′ 51′′ E, and at an altitude of 3,428 m (Fig. 3-1). This winter pasture is close to the burrows of plateau pikas and is surrounded by a complex mosaic of disturbed patches of different sizes. Heavily degraded meadow (HQ3-H) was located at 33 °55′ 00′′ N and 102° 09′ 15′′ E, and an altitude of 3,433 m (Fig. 3-1). This area is characterized by a natural pit, ranging from 50 m × 50 m, where livestock are concentrated at night to avoid the cold. Comparison among these three study sites would be beneficial to the objective of the present study.

### 3.2.2 Identification of vegetation types and intensity in the studied degraded farms

The identification of vegetation was undertaken according to local experts and the Luqu Meadow Research Station. Five quadrats of 1 m×1 m were outlined at each site, and plant coverage (C; %) and height (H; cm) of each species in each site were measured using a modified Penfound–Howard method. Following this, the summed dominance ratio, $SDR_2$ (Yamamoto et al., 1995), was calculated to compare vegetation between communities. $SDR_2$ was obtained using the following equation:

$SDR_2=(C'+H')/2$

where C′ and H′ are the relative coverage value and relative plant height of each species to the respective maximum values of all communities, respectively.

Plant species diversity was calculated at each site using Shannon-Wiener's diversity index *H'* (Magurran, 1988):

$$H' = -\sum (Pi)\,(log_2 Pi)$$

$$Pi = ci/C$$

where *ci* was the coverage of the *i*th species in a plot, and *C* was the total coverage of all species in the plot.

### 3.2.3 Determination of soil properties

#### 3.2.3.1 Analysis of soil physicochemical properties

Soil surveys were conducted in order to identify soil profile morphological characteristics, according to the Guidelines for Soil Description (FAO, 2006) and soil classification following the WRB (IUSS Working Group WRB. 2014). Soil samples from each horizon of the three soil profiles were collected for physicochemical analysis. Samples were crushed with a mortar and pestle after being air dried and passed through a 2 mm sieve. Calculation of the results of soil analysis was based on "oven-dry" soil. The moisture of the sample should be determined shortly before soil analysis (Reeuwijk, 2002). Soil particle size distribution was determined by the pipette method (Reeuwijk, 2002). Organic carbon (OC) and total nitrogen (TN) contents were determined using the dry combustion method with an NC analyzer (SUMIGRAPH NC-900, Sumika Chemical Analysis Service, Tokyo, Japan) after pretreatment by 1/3 M $H_3PO_4$ to remove inorganic carbon. The carbonate content was determined using the Rapid Titration Method (Reeuwijk, 2002). Soil pH values were determined with a glass electrode pH meter (HM-30R, DKK-TOA Co., Tokyo, Japan). Electric conductivity (EC) was determined with an EC meter (CM-30R, DKKTOA Co., Tokyo, Japan). Exchangeable bases ($Ca^{2+}$, $Mg^{2+}$, $K^{+}$, $Na^{+}$) were extracted with 1 M $CH_3COONH_4$ (pH = 7) solution by Atomic Absorption Spectrophotometry, and cation exchangeable capacity (CEC) was measured using the semi-micro Schollenberger Method (Schollenberger and Simon, 1945). Extractable iron, aluminum, silicon, and calcium were measured by selective dissolution analysis, which comprises the acid ammonium oxalate dissolution method (samples termed $Fe_o$, $Al_o$, and $Si_o$), the sodium dithionite citrate dissolution method (samples termed $Fe_d$, $Al_d$, $Si_d$, and $Ca_d$), and the sodium pyrophosphate dissolution method (samples termed $Fe_p$, $Al_p$, $Si_p$, and $Ca_p$) (Reeuwijk, 2002). Moreover, the extractable Fe, Al, Si, and Ca were determined by Plasma Emission Spectrometer (Perkin Elmer, Optima 7300DV).

### 3.2.3.2 Preparation and description of soil thin sections

For making soil thin section, undisturbed 100 ml core samples were taken from 0 to 5cm surface soils of the three soil profiles. These thin sections were prepared according to the study by Nagatsuka and Tamura (1986). The intact soil samples were freeze-dried and impregnated with a polyester resin (Polyester resin A and B, MARUTO, Japan.) and benzyl peroxide (Embedding agent, MARUTO, Japan), then, after using a vacuum impregnation apparatus for more than three days, the samples were cured under a fume hood for up to three months, and soil thin sections were cut using a diamond cutter. Samples were then ground using abrasion (C3000; Maruto) (first polishing) and bonded onto a glass slide (5 cm×5 cm) with epoxy resin. A second polish was performed with abrasive paper and a lapping machine in order to reduce the thickness of the samples to approximately 30 μm. Thin sections were examined using an OLYMPUS BH-2. Soil thin section descriptions were made according to the Handbook for Soil Thin Section Description (Bullock et al., 1985).

### 3.2.3.3 Quantifying porosity and measurement of fractal dimensions

Optical microscopy images of soil thin sections were used for image analysis. Image processing was divided into two steps. Firstly, the open-source software ImageJ (National Institutes of Health, USA) was used for quantifying porosity, wherein the color images were converted into black and white binarized images in which transparent minerals were manually marked by comparing the original images in PPL and XPL. Secondly, automatic image analysis (fractal 3, National Agriculture and Food Research Organization, JP) was used to measure the void surface fractal dimensions by the box counting method (Dathe et al., 2001; Nakatsuka et al., 2016).

The objects are covered by orthogonal line grids of increasing lattice constant. The number (N) of meshes (boxes) containing parts of the structure are calculated for each box size (equal to the lattice constant $\varepsilon$). According to the macro-scale increase in the box size ($\varepsilon$) at selected step sizes, and for each box size, those boxes containing at least one pixel of the contour line were counted (N). This count number N (ε) depended on the box size (ε) and fractal dimension D according to Eq. (1).

$$N(\varepsilon) \propto \varepsilon^{-D}$$

Thus, for fractal objects a double-logarithmic plot yields a straight line according to Eq.

$$log\, N(\varepsilon) = -D\, log\, \varepsilon + a$$

and the fractal dimension D can be determined as the absolute value of its slope. The constant $a$ describes the ordinate intercept. The box size (ε) was chosen from 4, 8, 16, 32, 64, 128, and 256 pixels and analyzed by fractal 3 (Sasaki et al., 1994).

## 3.3 Results

### 3.3.1 Vegetations in the studied farms with varying degrees of soil degradation

Mean coverage was highest in HQ1-L (94%), and the number of plant species in HQ1-L was larger than in either HQ2-M or HQ3-H (Fig. 3-2) (Table 3-1). Vegetation was scarce in HQ2-M and HQ3-H. The Shannon–Weiner index ranged between 1.92 and 2.55, the highest value exit in HQ1-L corresponding to the highest total number of species (13) (Table 3-3). According to $SDR_2$ values, the dominant plant species were determined at each site, and *Kobresia kansuensis* was found to be dominant at HQ1-L and HQ2-M (Table 3-1).

### 3.3.2 Morphological properties of the studied soils with varying degrees of degradation

Soil surveys showed that the OA horizon existed in HQ1-L and HQ2-M, but was not complete in HQ2-M. The OA horizon shows a strong enrichment of felty root biomass, and the texture suggests considerable firmness making the material difficult to dig. The crumb structure exists in topsoil with the OA horizon (Fig. 3-2) (Table 3-2). Soil structure suggested that the aggregation was well-developed in HQ1-L and HQ2-M. The soil texture was different at each site: heavy clay; sandy loam; and sand, respectively (Fig. 3-2) (Table

3-2). This shows that soil texture deteriorates with an increase in grazing intensity. Soil of HQ1-L was very hard in dry conditions whereas HQ2-M and HQ3-H showed slightly increased hardness under dry conditions. The clay content of the topsoil was 17.8%, 14.1%, and 10.0% in HQ1-L, HQ2-M, and HQ3-H (Fig. 3-2) (Table 3-2), respectively. Silt contents were 15.7%, 14.2%, and 7.7%, and sand contents were 46.2%, 52.0%, and 62.0% (Table 3-2), respectively. The results of particle size distribution suggested that HQ1-L existed with high clay and silt contents and this site was classified as clay loam. HQ2-M and HQ3-H showed lower clay and silt contents with higher sand contents. The highest moisture contents observed were in HQ1-L, followed by HQ2-M and HQ3-H. Moisture contents of topsoil were 13%, 2.9%, and 1.1% in HQ1-L, HQ2-M, and HQ3-H (Table 3-2), respectively.

Through morphological analysis of the soil profile, affected by rodent activity and increased grazing intensity, the OA horizon was shown to be intact, incomplete, and disappearing in HQ1-L, HQ2-M, and HQ3-H, respectively. A carbonate accumulated horizon (Bk) appeared in subsoil of HQ1-L and HQ3-H; indeed, the soil color of the Bk horizon in HQ1-L was gray and the brightness lighter than another Bk horizon in HQ3-H (Fig. 3-2) (Table 3-2).

### 3.3.3 Chemical characteristics of studied soils with varying degrees of degradation

The pH ($H_2O$) values of the topsoil were 6.27, 6.65, and 6.95 in HQ1-L, HQ2-M, and HQ3-H (Table 3-3), respectively, and increased with depth, the highest value being accompanied by a large amount of carbonate accumulation in the Bk horizon. EC values of topsoil were 0.098, 0.108, and 0.046 dS $m^{-1}$ and of subsoil were 0.087, 0.020, and 0.064 dS $m^{-1}$ in HQ1-L, HQ2-M, and HQ3-H (Table 3-3), respectively. Higher EC values were recorded in the OA horizon and in horizons characterized by carbonate accumulation.

OC contents of topsoil were 70.7, 81.9, and 25.7 g $kg^{-1}$ and TN contents were 5.7, 6.9, and 2.5 g $kg^{-1}$ in HQ1-L, HQ2-M, and HQ3-H (Table 3-3), respectively. OC and TN contents typically decreased with increasing soil depth, and also decreased with the aggravation of degree of degradation. The C/N ratio was higher in the topsoil of HQ1-L, and lower in HQ2-M and HQ3-H. Carbonate contents ranged from 0.57% to 35.12%, and the soil color change to gray in Bk horizon (Table 3-3). The exchangeable cations were dominant, with $Mg^{2+}$ and $Ca^{2+}$ in all study sites, and the highest CEC values were observed in HQ1-L, followed by HQ2 -M and HQ3-H (Table 3-3). Dissolution of $Fe_p$, $Al_p$, and $Si_p$ was significantly lowest, and the averages of topsoil were 72%, 84%, and 34% in HQ1-L, HQ2-M, and HQ3-H (Table 3-4). The dissolution of $Si_o$, $Si_p$, and $Si_d$ was lowest in each site.

### 3.3.4 Soils of the studied farms with varying degrees of soil degradation

Soil classification was made according to the internationally recognized WRB system (IUSS Working Group WRB. 2014) method. In this study, soil from all study sites showed properties of the mollic horizon. The verification standard of mollic horizon in the WRB system was as follows: the mollic horizon (from Latin mollis, soft) is a thick, dark-colored surface horizon with a high base saturation and a moderate to high content of organic matter.

The base saturation is more than 50% and has high OC content at each site. Its dark color was caused by the accumulation of OC, in most cases a well-developed structure (crumb structure also exists in HQ1-L and HQ2-M, and fine subangular blocky structure exist in HQ3-H).

Therefore, all study sites featured the mollic horizon. The OA horizon existed in HQ1-L with a well-developed crumb structure. There was also an amount of secondary carbonate accumulate in HQ1-L and HQ3-H, but the soil color of the Bk layer of HQ1-L changed to gray. There are incomplete or destroyed OA layers in HQ2-M and HQ3-H. In conclusion, the HQ1-L soils in Hequ were Luvic Phaeozems; the HQ2-M soils in Hequ were Haplic Phaeozems; the HQ3-H soils in Hequ were Calcaric phaeozems (IUSS Working Group WRB. 2014).

### 3.3.5 Micromorphological characteristics of the top horizon

HQ1-L was dominated by the crumb structure (Fig. 3-3a, b), HQ2-M showed a complex structure with crumb structure and intergrain micro-aggregate structure (Fig. 3-3c, d), and HQ3-H was dominated by intergrain micro-aggregate structures (Fig. 3-3d, e). 10 images per sample for calculating porosity were analyzed using image J, and the total porosity was found to be approximately 8.45 ($\pm$ 1.01), 7.67 ($\pm$ 0.66), and 5.68 ($\pm$ 0.73) in HQ1-L, HQ2-M, and HQ3-H (Fig 3-5) (Table 3-5); the void percentage reduces with meadow degradation.

In terms of the basic organic components and pedofeatures, the abundance of basic organic materials was 30%, 25%, and 5% in HQ1-L, HQ2-M, and HQ3-H (Table 3-5), and the main component was root. In HQ3-H, however, there was very little organic matter. Living roots had internally filled cells and a yellowish-brown epidermis (cortex), showing birefringence (Fig. 3-4a, b), whereas dead roots have only the yellowish brown to brownish black cortex remaining (Fig. 3-4f), thus the prevailing portion of root matter originates from living roots in HQ1-L and HQ2-M, but mostly dead roots in HQ3-H. The soil animal excrements, which show the activity of soil animals, exists in HQ1-L (Fig. 3-4g, h) and HQ2-M (Fig. 3-4i), and as an aging excrement in HQ2-M. No pedofeatures resulting from excrements were noted in HQ3-H.

### 3.3.6 Fractal dimensions of soil microstructure

There was a strong linear relationship between log10[N(ε)] and log10(ε) in all study sites (Fig. 3-5). Results show that the microstructure of all studies has fractal characteristics, thus it is reasonable to calculate its fractal dimension. The fractal dimensions decreased with soil degradations.

## 3.4 Discussions

### 3.4.1 Soil properties and vegetation with meadow degradation degree

The value of vegetation coverage was 94% in HQ1-L, higher than HQ2-M (71%), HQ3-H (21%) (Fig. 3-2) (Table 3-1). This difference may be caused by a ban on grazing during the growing season at HQ1-L, increasing populations of native small mammals (e.g. *Ochotona curzoniae*) at HQ2-M, the large number of livestock which causing severe damage to the OA layer at HQ3-H.

Currently, Hequ farm is subject to environmental degradation and decreasing carrying capacity due to natural and anthropogenic impacts. At HQ2-M, plateau pikas act as foragers of vegetation. Their burrowing behavior destroys surface vegetation and creates a complex mosaic of disturbed patches of different sizes (Smith and Foggin, 1999;Davidson and Lightfoot, 2008; Wu et al., 2015; Yu et al., 2017). Human factors mainly refer to overgrazing, the increase in the number of livestock, causing devastating damage to the surface vegetation due to trampling and foraging. Meanwhile, overgrazing has led to increased populations in small mammals including plateau pika (Wang et al., 2007b). In this study, disturbance of pika was shown in HQ2-M, due to burrow nesting, destroying the soil surface, resulting in an incomplete OA layer.

*Kobresia* are mainly distributed across the south and east of the QTP, and perennial herbs are dominant in the alpine meadow community (Zhao et al., 2006). However, with the aggravation of degradation, the SDR2 value of *Chenopodium iljinii* showed a rising trend, reaching its peak at HQ3-H (Table 3-1). The analysis of community structure change under different degradation has shown that the degradation of alpine meadows community is a process in which the dominant species (protophytic communities) are weakened. During this process new species infiltrated and gradually become the dominant species overtime. Tang et al. (2011) showed that unique species in the communities of the eastern QTP are found in drought durable and sand texture habitats, such as *C. iljinii*, indicating that the community structure and soil conditions of heavily degraded meadow have changed. So that, *C. iljinii* can be a good indicator of degradation in my study site.

From the results of soil survey and physicochemical properties, HQ1-L having OA horizon had higher contents of moisture, clay, OC, TN and CEC as compared with HQ2-M and HQ3-H sites. Increased grazing intensity aggravated animal trampling, directly influencing soil surface properties, increasing bulk density, and causing soil loss by water and wind erosion. This changed the spatial distribution of pores and reduced the stability of soil aggregates (Villamil et al., 2001). Most of the underground phytomass can help to store more carbohydrates for plants to grow rapidly after alternation of freezing and thawing, and can promote the rapid absorption of water and nutrients under harsh climates in alpine and non-alpine tundra ecosystems (Wielgolaski and Goodall, 1997). Thus, my results suggest that the developed root system of OA horizon may be responsible for the direct relationship between the moisture content and the existence state of OA horizon, also, the soil texture was clay loam with good water retention and storage capacity in my study site (Table 3-2). From my results, vegetation coverage, vegetation composition and soil properties (Table 3-1 and Table 3-2), it can be concluded that all the study sites were subject to varying degrees of soil erosion. Especially good soil condition was accompanied by the presence of the OA horizon.

There was a strong correlation of the OA horizon and soil pH value (Table 3-3) since, when topsoil is destroyed, subsoil with higher pH values is exposed and forms new surface soil, such that the pH value of surface soil increases with the degree of degradation. In HQ1-L and HQ2-M, the change of upper soil pH value was not obvious, because the OA layer exists. Soil OC and TN were significantly lower in HQ3-H in my study (Table 3-3). Wang et al. (2007a) reported the severe loss of SOC and TN in badly degraded ecosystems, for which the reasons can be attributed to: (1) destruction of the mattic epipedon leading to exposure of the subsoil layer and increased hazard of soil erosion by wind and rodents; (2) concomitant reduction in the return of plant residues to soil (Nunes et al., 2012; Peng et al., 2015). The value of CEC was highest in topsoil for each site and decreased with depth, although this also decreased with an increase in degradation (Table 3-3). Therefore, the values of exchangeable cations, CEC, TN, and OC may be used as an index of soil fertility to measure the degree of grassland degeneration.

Selective extraction techniques have distinct abilities for the dissolution of various iron and aluminum phases, such as the non-crystalline Fe and Al oxides that are mainly extracted by acid ammonium oxalate dissolution, the strong reductant of dithionite dissolving more Fe than any other extraction, and sodium pyrophosphate dissolving Fe and Al associated with soil organic matter (Parfitt and Childs, 1988; Reyes and Torrent, 1997; Aran et al., 2001; Wagai et al., 2011). In this study, the ranges of $Fe_d$ were 5.13~11.23 mg $g^{-1}$ (Table 3-4), i.e., significantly higher than $Fe_o$, indicating that some crystalline iron oxides are present (Parfitt and Childs, 1988) in addition, decreased with an increase in degradation. The $Al_d$ values are like the $Al_o$ values and higher than $Al_p$ values, indicating that some Al-humus complexes and poorly crystalline minerals are extracted from all study sites (Parfitt and Childs, 1988). The value of $Ca_d$ was highest in the Bk horizon due to the significant carbonate accumulation.

### 3.4.2 The micromorphological characteristics with meadow degradation degree

In this study, I found that as the degree of degradation increases, the porosity decreases, and the number of soil aggregates decreases (Table 3-5) (Fig. 3-2). The grade of pedality also decreases, as does the microstructure (Fig. 3-3) (Table 3-1). Peth et al. (2008) in their study reported that pore size and distribution in intra-aggregate were of great importance for water and ion flux rates, and thus in the control of C sequestration and bioremediation. Soil structure is the main factor affecting plant growth, which determines the depth that roots can penetrate, store water in the soil, and regulate the movement of air, water, and soil animals (Pagliai et al., 2004). Therefore, I considered the HQ1-L was good soil condition with higher abundance of voids, follow by HQ2-M and HQ3-H (Table 3-5) (Fig. 3-2).

Whether it is the residue of organic matter, the activity of soil animals, or the number of aggregates, my results suggest that they all show a downward trend with increasing degradation, and these results agreed with those of the previous study. Balesdent et al. (2000), Six et al. (2002), Horn et al. (2005) and Nakatsuka et al. (2016) in their study have reported that the fresh organic residues, microorganisms, and clay particles are key factors in the formation of early aggregates. Thus, From the results of clay contents (Table 3-2) and plant residues (Fig. 3-3) (Table 3-5) suggest that the accumulation of organic residues and clay content is directly or indirectly associated with soil degradation. The surface soil-forming processes are mainly affected by the accumulation of partially decomposed plant fragments and faunal activity (Brewer and Pawluk, 1975); therefore, the development of root systems will affect the soil microstructure. This suggests that the microstructure of HQ1-L and HQ2-M was developed under influence from a well-developed rhizosphere, and that an increased root biomass contributed to an increased number of pore spaces.

Kampichler. (1999) reported that the diverse range of options for applying fractals to soil zoological research suggests that high fractal dimension corresponds to a more complex pore structure. My results suggest that for the soil microarthropods, since these animals are incapable of digging and thus are confined to the surfaces of soil crevices, HQ1-L is more conducive to soil fauna survival, followed by HQ2-M, and HQ3-H.

### 3.5 Conclusion

The results obtained in this study indicated a strong relationship between the presence of the OA horizon and soil physicochemical properties and showed that *K. kansuensis* was one of the main plants forming the OA horizon due to its developed root system. The profile morphologies demonstrated that the OA horizon gradually disappeared as the degree of degradation increases. Exchangeable cations, CEC, TN, and OC decreased with increasing soil degradation; however, pH value was exactly the opposite. The soils were classified as Luvic Phaeozems, Haplic Phaeozems, and Calcaric phaeozems. The HQ1-L had a high porosity and high fractal dimensions, with the destruction of mattic epipedon, increased loss of clay and organic matter, and a change in soil microstructure from crumb structure to intergrain micro-aggregate structure, resulting in a restricted supply of mineral ions and free water to plant growth. Moreover, the activity of soil animals decreased with meadow degradation. Overall, the destruction of OA horizon will aggravate the soil degradation in Hequ pasture, which has already suffered from overgrazing and plateau pika. Therefore, protecting OA horizon in Qinghai-Tibet plateau should be given top priority.

Table 3- 1 Major species of the study sites. Showing the SDR2 value and Shannon-Wiener's index.

| Species | Life form | HQ1-L | HQ2-M | HQ3-H |
|---|---|---|---|---|
| Mean coverage(%) | | 94 | 71 | 21 |
| Number of species | | 13 | 5 | 6 |
| Shannon-Wiener's index | | 2.55 | 1.58 | 1.92 |
| *Kobresia kansuensis* | Per | 100 | 100 | 55 |
| *Taraxacum tibetanum* | Per | 8 | | |
| *Potentilla anserina* | Per | 37 | | |
| *Anaphalis lactea* | Per | 20 | | |
| *Tibetia himalaica* | Per | 21 | 20 | 9 |
| *Gentiana aristata* | Ann | 22 | | |
| *Anemone rivularis* | Per | 20 | 6 | 13 |
| *Gentiana straminea* | Per | 27 | | |
| *Saussurea pulchra* | Per | 6 | | |
| *Allium sikkimense* | Per | | | |
| *Comastoma pulmonarium* | Ann | 8 | | |
| *Chenopodium iljinii* | Ann | | 39 | 79 |
| *Plantago depressa* | Ann | 5 | 28 | 11 |
| *Ligularia virgaurea* | Per | 20 | | |
| *Elymus nutans* | Per | | | 44 |
| *Pedicularis cheilanthifolia* | Ann | 5 | | |

Per: Perennial; Ann: Annual

Table 3- 2 Brief description of the soil profile morphology.

| Depth | Horizon | Color | Clay,Silt,Sand % | Texture | Structure[a] | Roots[b] | Carbonate[c] | Moisture Content |
|---|---|---|---|---|---|---|---|---|
| HQ1-L | | | | | | | | |
| 0-10 | OA | 10YR2/2 | 22,20,58 | CL | ST,FI,CR | VF,M/F,M | N | 13.0 |
| 10-20 | A1 | 10YR2/3 | 24,19,57 | CL | MO,FI-ME,CR | VF,M/ F,C | N | 3.4 |
| 20-48 | A2 | 10YR2/3 | 22,19,60 | CL | MO,FI-CO,SB | VF,C/F,C | N | 2.6 |
| 48-72 | A3 | 10YR2/3 | 24,23,53 | CL | MO,ME-VC,SB | VF,F | N | 2.4 |
| 72-90 | A4 | 10YR2/2 | 25,26,49 | CL | MO,FI-CO,SB | VF,V | SL | 2.1 |
| 90-100 | Bk | 2.5Y4/4 | 25,28,46 | CL | MO,ME-CO,SB | VF,V | EX | 1.2 |
| HQ2-M | | | | | | | | |
| 0-10 | OA | 10YR2/2 | 18,18,65 | SCL | ST,FI-ME,CR | VF,M/F,M | N | 2.9 |
| 10-20 | A1 | 2.5Y3/2 | 10,12,78 | SL | MO,FI-ME,CR/MO,VF-FI,SB | VF,C/F,C | N | 2.9 |
| 20-35 | A2 | 10YR3/3 | 9,9,81 | SL | MO,ME-CO,SB | VF,F/F,F | N | 0.8 |
| 35-75 | Bw1 | 2.5Y3/3 | 6,14,80 | SL | MO,FI-ME,SB | VF,V/F,V | N | 0.7 |
| 75-100 | Bw2 | 2.5Y3/3 | 11,11,78 | SL | MO,ME-CO,SB | N | N | 0.7 |
| HQ3-H | | | | | | | | |
| 0-10 | A1 | 10YR2/3 | 11,9,80 | SL | WE,CO-VC,SB | VF,M/F,C | N | 1.1 |
| 10-24 | A2 | 10YR4/3 | 6,10,84 | S | WE,ME-CO,SB | VF,C/F,C | SL | 0.6 |
| 24-40 | Bk1 | 10YR4/3 | 8,7,85 | S | WE,ME-CO,SB | VF,F | SL | 0.5 |
| 40-75 | Bk2 | 10YR4/4 | 12,6,82 | S | WE,ME-CO,SB | VF,V | MO | 0.4 |
| 75-100 | Bk3 | 10YR4/4 | 2,11,87 | S | WE,ME-CO,SB | VF,V | MO | 0.4 |

[a] WE:weak; MO:morderate; ST:strong; VF:very fine; FI:fine; ME:medium;CO:coarse; VC:very coarse; CR:crumb; SB: subangular blocky

[b] VF:very fine; F:fine; V:very few; F:few; C:common; M:many.

[c] SL:slightly calcareous; MO:Moderately calcareous; EX:Extremely calcareous.

Table 3- 3 Chemical characteristics of the studied soil profiles

| Horizon | Depth | TN | OC | C/N | $CaCO_3$ | EC | pH | | Exchangeable Cation | | | | | CEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | $K^+$ | $Na^+$ | $Mg^{2+}$ | $Ca^{2+}$ | Total | |
| | [cm] | [g $kg^{-1}$] | | | % | dS $m^{-1}$ | $H_2O$ | KCl | [$cmol_c$ $kg^{-1}$] | [$cmol_c$ $kg^{-1}$] | [$cmol_c$ $kg^{-1}$] | [$cmol_c$ $kg^{-1}$] | [$cmol_c$ $kg^{-1}$] | [$cmol_c$ $kg^{-1}$] |
| HQ1-L | | | | | | | | | | | | | | |
| OA | 0-10 | 5.74 | 70.71 | 12.32 | 3.55 | 0.098 | 6.27 | 5.56 | 0.57 | 0.11 | 2.38 | 18.00 | 21.06 | 32.80 |
| A1 | 10-20 | 2.61 | 29.16 | 11.16 | 2.41 | 0.048 | 6.53 | 5.56 | 0.61 | 0.06 | 1.91 | 15.16 | 17.74 | 27.59 |
| A2 | 20-48 | 1.91 | 19.82 | 10.36 | 2.59 | 0.030 | 6.77 | 5.54 | 0.42 | 0.06 | 1.51 | 14.23 | 16.21 | 20.65 |
| A3 | 48-72 | 1.71 | 16.49 | 9.67 | 2.56 | 0.026 | 7.16 | 5.80 | 0.46 | 0.18 | 1.17 | 16.08 | 17.88 | 30.30 |
| A4 | 72-90 | 1.40 | 12.84 | 9.15 | 3.87 | 0.075 | 7.67 | 6.97 | 0.48 | 0.19 | 1.04 | 24.06 | 25.76 | 28.39 |
| Bk | 90-100+ | 0.42 | 6.99 | 16.67 | 35.12 | 0.087 | 8.64 | 7.69 | 0.22 | 0.04 | 0.86 | 32.23 | 33.34 | 12.40 |
| HQ2-M | | | | | | | | | | | | | | |
| OA | 0-10 | 6.93 | 81.88 | 11.82 | 4.1 | 0.108 | 6.65 | 5.90 | 0.71 | 0.12 | 2.50 | 25.58 | 28.91 | 27.60 |
| A1 | 10-20 | 2.32 | 24.76 | 10.69 | 1.96 | 0.034 | 6.99 | 6.02 | 0.25 | 0.07 | 1.23 | 10.62 | 12.17 | 13.24 |
| A2 | 20-35 | 1.04 | 8.10 | 7.79 | 0.57 | 0.020 | 7.09 | 6.05 | 0.19 | 0.01 | 0.63 | 4.44 | 5.28 | 6.08 |
| Bw1 | 35-75 | 0.83 | 6.41 | 7.70 | 0.87 | 0.014 | 7.40 | 6.12 | 0.15 | 0.01 | 0.72 | 5.57 | 6.46 | 6.84 |
| Bw2 | 75-100+ | 0.81 | 6.22 | 7.65 | 0.69 | 0.020 | 7.51 | 6.37 | 0.18 | 0.09 | 0.78 | 6.59 | 7.63 | 7.76 |
| HQ3-H | | | | | | | | | | | | | | |
| A1 | 0-10 | 2.47 | 25.74 | 10.41 | 1.62 | 0.046 | 6.95 | 6.19 | 0.53 | 0.01 | 5.45 | 12.83 | 18.82 | 16.58 |
| A2 | 10-24 | 0.95 | 6.59 | 6.96 | 1.18 | 0.033 | 7.31 | 6.60 | 0.46 | 0.07 | 3.17 | 39.28 | 42.99 | 6.45 |
| Bk1 | 24-40 | 0.77 | 5.28 | 6.88 | 0.61 | 0.031 | 7.67 | 6.82 | 0.49 | 0.11 | 0.64 | 11.46 | 12.70 | 5.24 |
| Bk2 | 40-75 | 0.38 | 1.69 | 4.46 | 4.84 | 0.068 | 8.36 | 7.82 | 0.24 | 0.11 | 0.43 | 15.67 | 16.45 | 2.68 |
| Bk3 | 75-100+ | 0.33 | 1.20 | 3.61 | 5.06 | 0.064 | 8.44 | 7.85 | 0.17 | 0.22 | 0.38 | 16.27 | 17.04 | 1.96 |

Table 3- 4 Extractable Fe, Al, Si and Ca

| Horizon | $Fe_o$ | $Al_o$ | $Si_o$ | $Fe_p$ | $Al_p$ | $Si_p$ | $Ca_p$ | $Fe_d$ | $Al_d$ | $Si_d$ | $Ca_d$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | mg $g^{-1}$ | | | mg $g^{-1}$ | | | | mg $g^{-1}$ | | | |
| HQ1-L | | | | | | | | | | | |
| OA | 2.41 | 1.25 | 0.57 | 0.66 | 0.97 | 0.54 | 5.40 | 8.80 | 1.25 | 2.06 | 4.99 |
| A1 | 2.74 | 1.62 | 0.68 | 0.79 | 1.18 | 0.42 | 3.53 | 10.56 | 1.54 | 2.19 | 3.87 |
| A2 | 2.64 | 1.56 | 0.63 | 0.65 | 1.09 | 0.34 | 3.23 | 10.74 | 1.36 | 1.92 | 3.68 |
| A3 | 2.72 | 1.68 | 0.80 | 0.66 | 1.06 | 0.42 | 3.86 | 11.23 | 1.31 | 2.41 | 4.14 |
| A4 | 2.67 | 1.70 | 1.09 | 0.40 | 0.95 | 0.17 | 5.49 | 10.64 | 1.28 | 3.37 | 7.34 |
| Bk | 1.93 | 0.71 | 0.52 | 0.85 | 0.59 | 0.10 | 4.65 | 5.13 | 0.38 | 0.87 | 70.32 |
| HQ2-M | | | | | | | | | | | |
| OA | 3.00 | 0.87 | 0.63 | 0.92 | 0.86 | 0.73 | 7.34 | 8.57 | 0.90 | 2.16 | 8.08 |
| A1 | 2.41 | 0.76 | 0.49 | 0.47 | 0.79 | 0.16 | 2.59 | 9.05 | 0.94 | 1.78 | 3.45 |
| A2 | 2.19 | 0.59 | 0.46 | 0.23 | 0.65 | 0.08 | 1.30 | 8.27 | 0.79 | 1.79 | 1.77 |
| Bw1 | 2.27 | 0.68 | 0.50 | 0.23 | 0.66 | n.d.[a] | 1.38 | 8.86 | 0.80 | 1.97 | 1.88 |
| Bw2 | 2.25 | 0.69 | 0.53 | 0.19 | 0.64 | n.d.[a] | 1.54 | 9.26 | 0.82 | 2.05 | 2.19 |
| HQ3-H | | | | | | | | | | | |
| A1 | 1.87 | 0.55 | 0.44 | 0.27 | 0.64 | 0.11 | 2.87 | 7.63 | 0.63 | 1.56 | 3.25 |
| A2 | 1.62 | 0.44 | 0.40 | 0.23 | 0.67 | 0.08 | 1.76 | 7.38 | 0.52 | 1.53 | 2.17 |
| Bk1 | 1.64 | 0.43 | 0.45 | 0.08 | 0.56 | n.d.[a] | 1.59 | 7.07 | 0.50 | 1.52 | 1.96 |
| Bk2 | 1.50 | 0.31 | 0.43 | 0.04 | 0.54 | n.d.[a] | 3.85 | 6.72 | 0.51 | 1.67 | 11.14 |
| Bk3 | 1.44 | 0.16 | 0.42 | 0.04 | 0.52 | n.d.[a] | 4.19 | 7.04 | 0.45 | 1.64 | 11.88 |

[a] n.d.: not detected

Table 3- 5 Characteristics of the soil micromorphological

| | | HQ1-L | | HQ2-M | | HQ3-H | | |
|---|---|---|---|---|---|---|---|---|
| | | OA(0-5cm) | | OA(0-5cm) | | A1(0-5cm) | | |
| Dominant microstructure[a] | | Cr | | Cr and Ima | | Ima | | |
| | $c/f_{10um}$[b] | Ch | | Ch | | En | | |
| Aggregation | Peds[c] | Cr | Gr | Cr | Gr | Cr | | Gr |
| | Grade of pedality[d] | St | St | St | Mo | Mo | | Mo |
| | Abundance (%) | 80 | 20 | 65 | 35 | 40 | | 60 |
| | Size (mm) | 1-2 | <0.5 | 0.2-2 | <0.5 | <0.5 | | <0.5 |
| Voids | Type[e] | Cdp | | Cxp | | Cxp | | |
| | Abundance[f] | 8.45 (±1.01) | | 7.67 (±0.66) | | 5.68 (±0.73) | | |
| Basic organic components | | | | | | | | |
| Coase fraction (>10um) | Type[g] | Ro | Lr | Ro | Lr | Ro | Lr | Ch |
| | Abundance (%) | 25 | 5 | 20 | 5 | 2 | 2 | 1 |
| Fine material (<10um) | Type[h] | Lop | | Lop | | Lop | | |
| | Abundance[i] | Vf | | Vf | | Vf | | |
| Excrement pedofeatures | Type[j] | IE | | AE | | - | | |
| | Abundance[k] | 5 | | 2 | | - | | |
| Fractal dimension of voids | | 1.65 | | 1.49 | | 1.3 | | |

[a] Cr:crumb; Ima:intergrain micro-aggregate.
[b] Ch:chitonic; En:enaulic.
[c] Cr:crumbs; Gr:granules.
[d] St:strong; Mo:moderately.
[e] Cdp:compound packing; Cxp:complex packing.
[f] Mean (±standard deviation).
[g] Ro:roots; Lr: leaf residues; Ch: charcoals.
[h] Lop:little organic pigment
[i] Vf:very few(<5 in soil thin section)
[j] IE:intact excrement; AE:aging excrement
[k] The number of excrement found in the thin section.

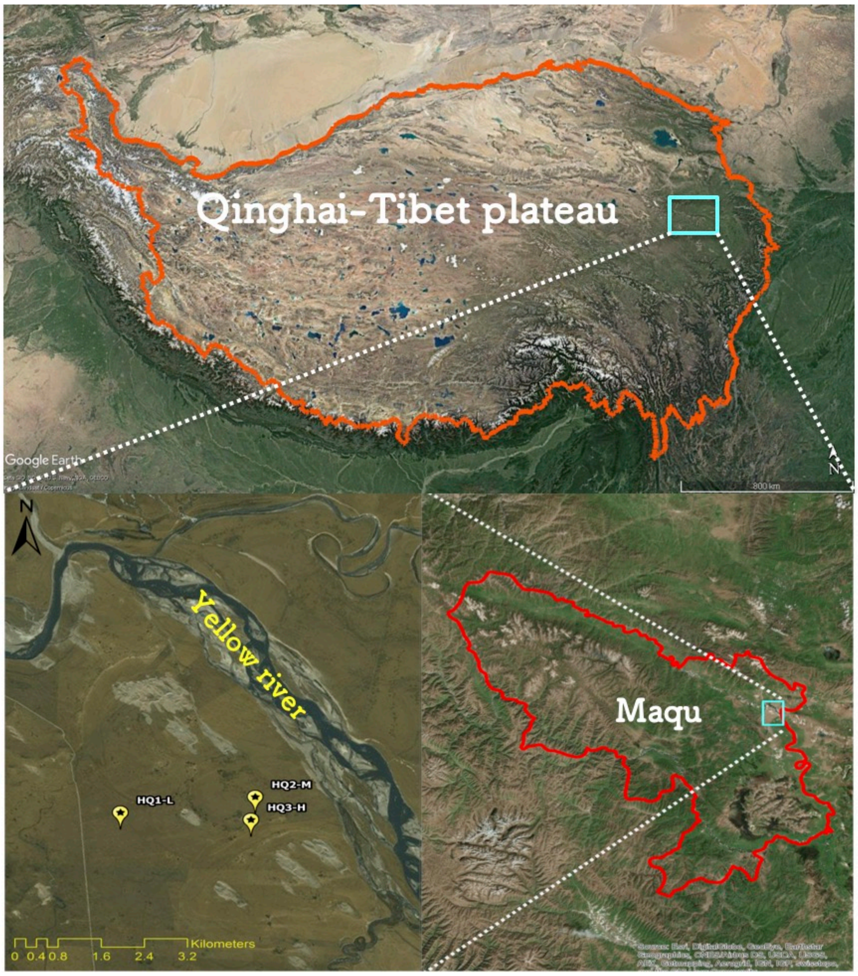


Figure 3- 1 Location of study sites in Maqu within QTP

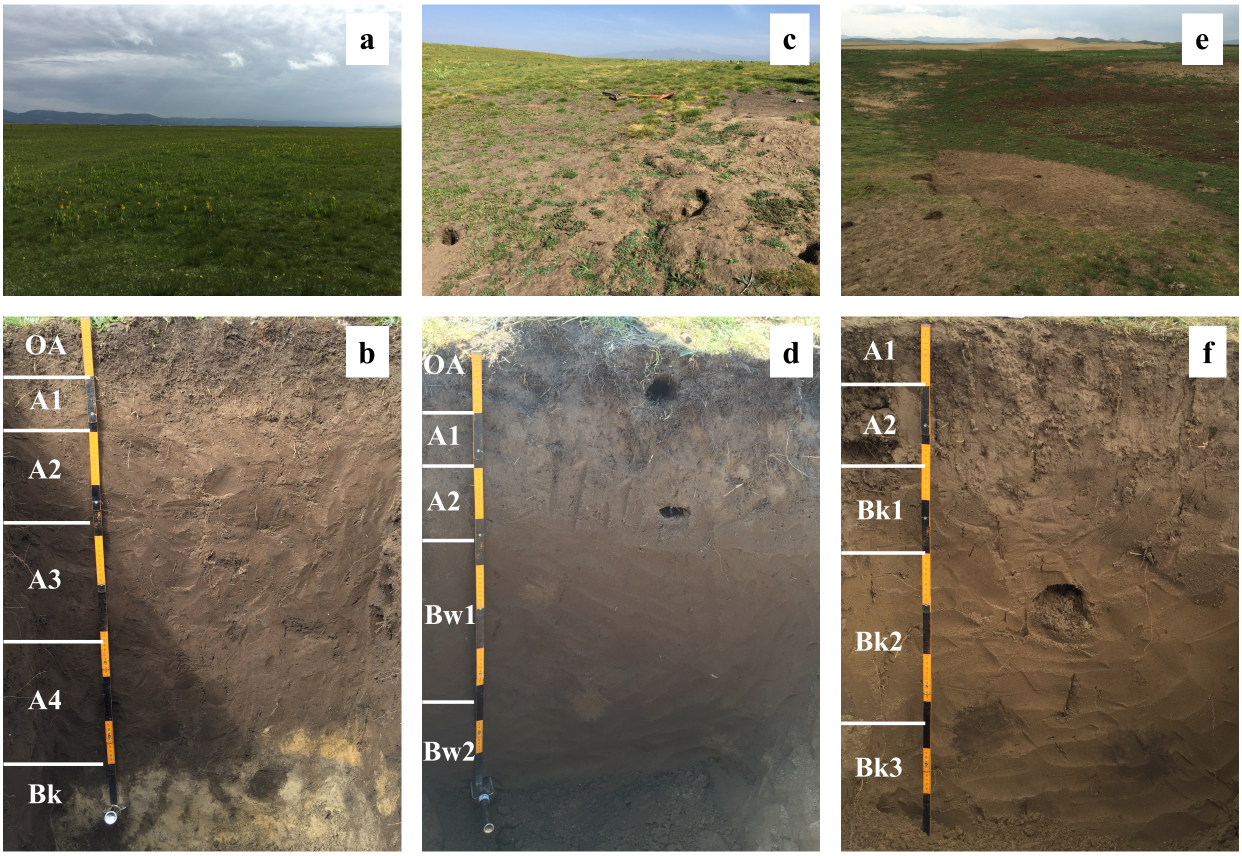


Figure 3- 2 Photographs of the profiles investigated

(a) 94% vegetation coverage at HQ1-L. (b) The Luvic Phaeozems at profile HQ1-L (length of the ruler=100cm). (c) 71% vegetation coverage at HQ2-M. (d) The Haplic Phaeozems at profile HQ2-M (length of the ruler=100cm). (e) 21% vegetation coverage at HQ3-H. (f) The Calcaric Phaeozems at profile HQ3-H (length of the ruler=100cm).

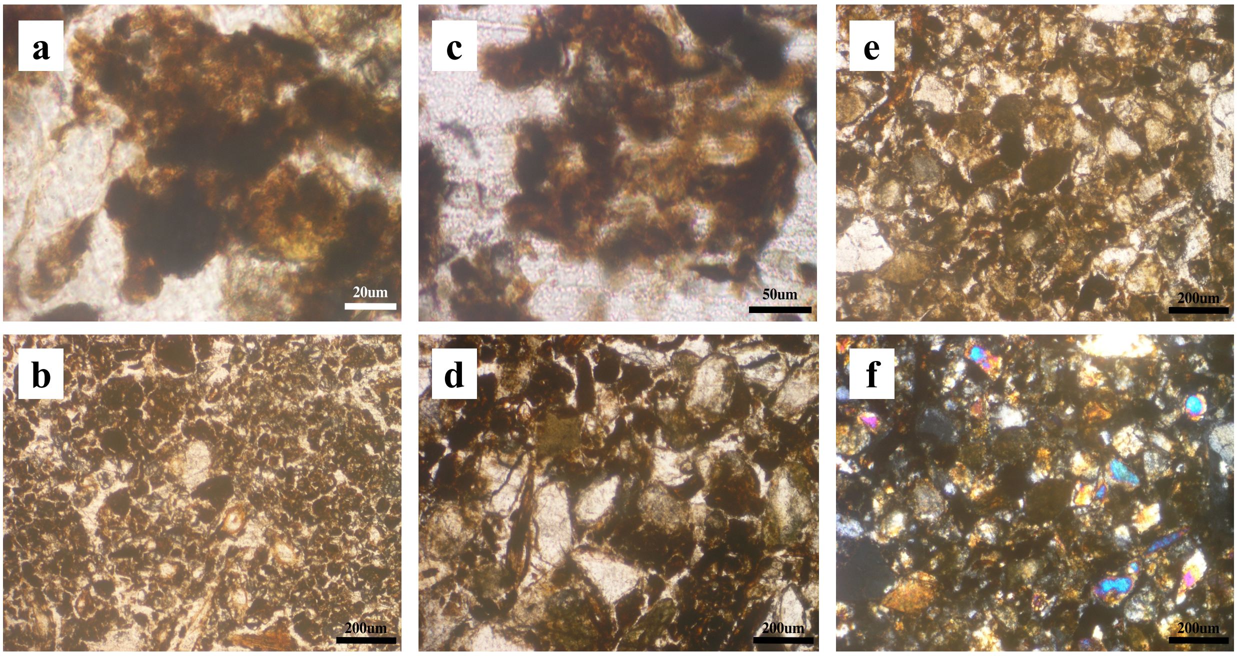


Figure 3- 3 Microstructure of top horizon

(a) (b) Crumb structure in HQ1-L by PPL. (c) Granular structure in HQ2-M by XPL. (d) Intergrain micro-aggregate structure in HQ2-M by PPL. (e) (f) Intergrain micro-aggregate structure in HQ3-H by PPL and XPL.

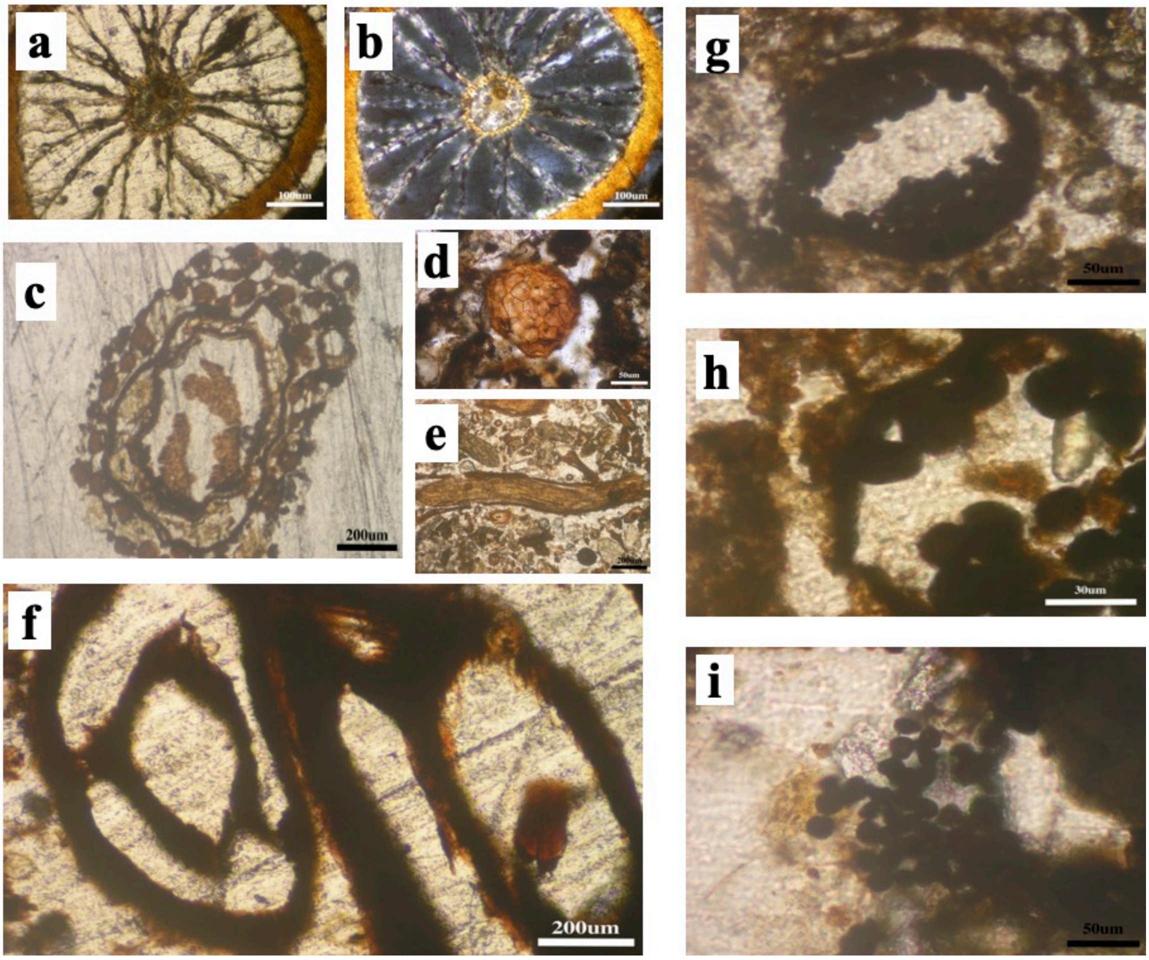


Figure 3- 4 Photomicrographs from the top horizon
(a) (b) Living roots in HQ1-L by PPL and XPL. (c) roots residues in HQ2-M by PPL. (d) Tissue fragment in HQ2-M by PPL. (e) Leaf tissue fragment in HQ3-H by PPL. (f) Mostly dead roots in HQ3-H by PPL. (g)(h) Intact excrement pedofeature in HQ1-L. (i) Aging excrement pedofeature in HQ2-M.

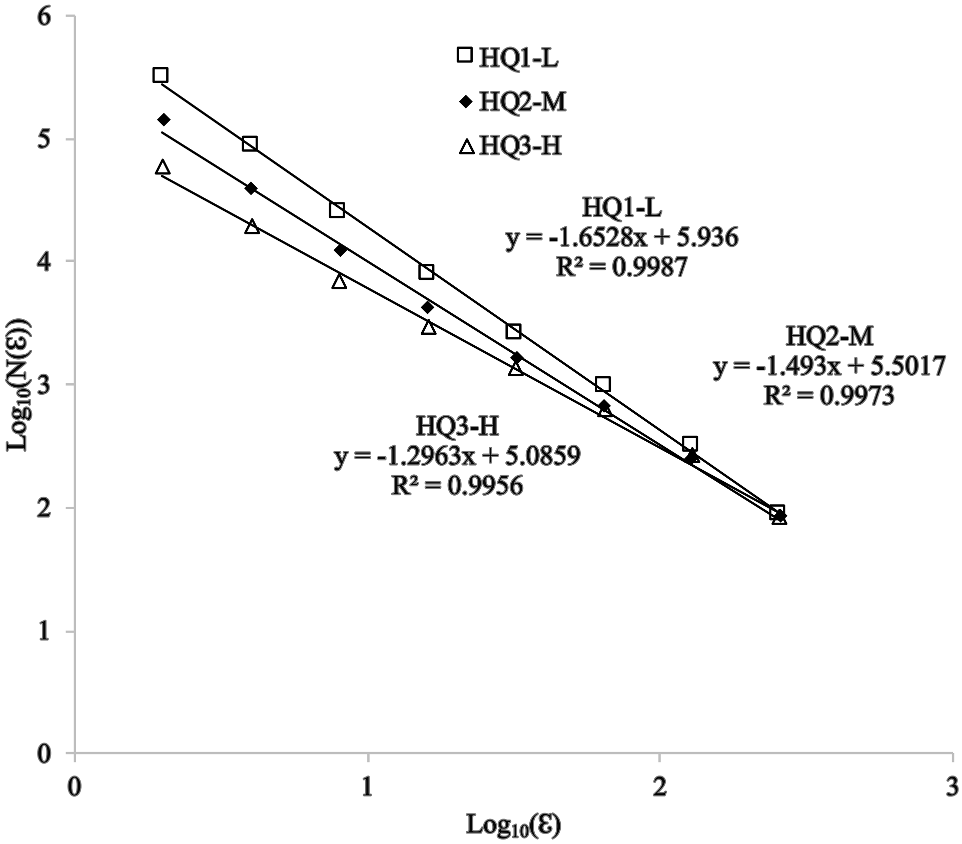


Figure 3- 5 Fractal analysis of the top horizon of HQ1-L, HQ2-M and HQ3-H

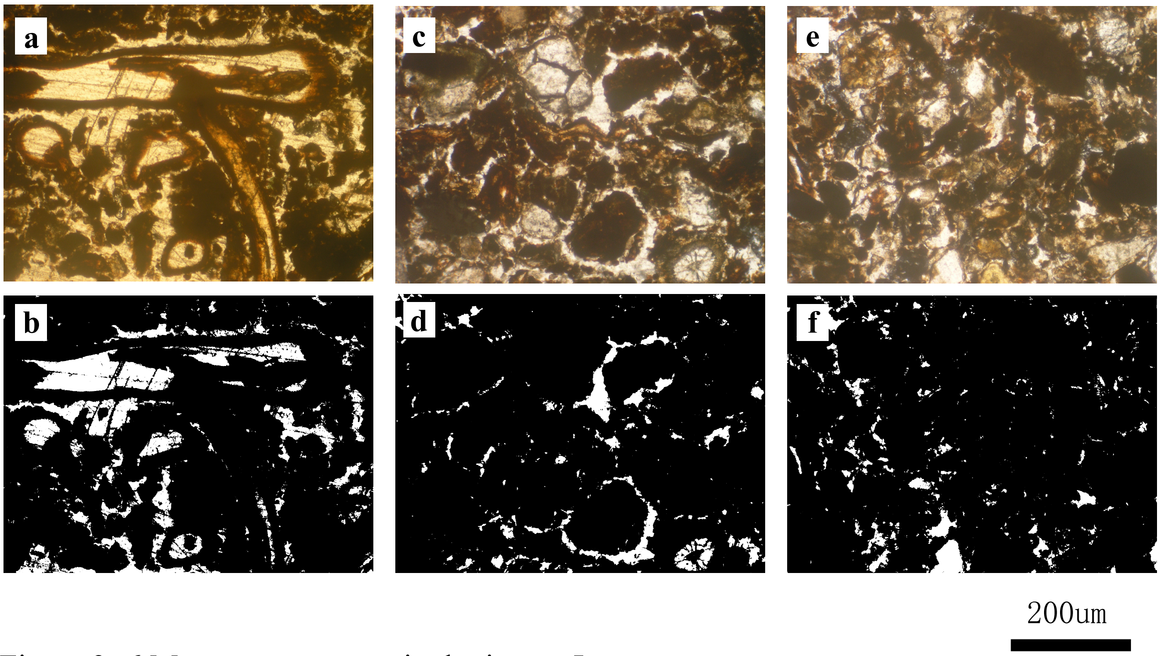


Figure 3- 6 Measurement porosity by image J

(a)(b) Compound packing voids in HQ1-L by PPL and binary (8.07 (±0.68)). (c)(d) Compound packing voids in HQ2-M by PPL and binary (7.67 (±0.67)). (e)(f) Complex packing voids in HQ3-H by PPL and binary (5.67 (±0.73)).

## Chapter 4

## General Discussion

### 4.1 Pedogenesis of Alpine Meadow

In the Hequ and Langmu regions, the morphology of soil profiles showed OA+A+Bk/Bw horizons, and the total thickness of solum above 100 cm, soils were classified as Phaeozems. There are well-developed Bk or Bw horizons, the carbonate was accumulated in subsoils, however the soil profile of HQ2-M without carbonate accumulation, this could be attributed to the distribution of a large number of rodent burrows at the surface, increasing the water infiltration rate(Wilson and Smith, 2014), and the carbonate accumulation perhaps appearing deeper underground. The soil profiles of Laneika was showed A+AB+B horizon, the difference is that there is no cover of OA horizon. In the Gongba, the soil profile is showed OA+A+Ck lacking B horizon, and the total thickness of solum are 32-45 cm, the soil was classified as Cambisols. Although there is the lack of B-horizon in this area, but the organic matter surface layer reaches above 32 cm.

Compared to Gongba and Hequ areas, their pedogenic factors such as climate (altitude), topography (slope), and vegetation (mattic epipedon) are similar, and since the sample sites in the Hequ area have different degrees of degradation problems, the degree of degradation in HQ1-L is similar to G-C as measured by vegetation cover, whereas the values of OC and TN ,CEC and EC in G-C lower than HQ1-L, and combined with soil morphological characteristics, HQ1-L has a higher soil development than G-C. In the Gongba region, the soil lacking B horizon, the surface layer direct cover C horizon, this indicates that the soil formation time here was relatively short. Yang et al. (2016) reported that the fine soil material of the mattic epipedon is mainly from the Holocene loess deposits, and the continuous accretion of the fine soil layer is the key process of pedogenesis on the north-eastern QTP. Due to its geographical location, Gongba is closer to the Loess Plateau, so the soil-forming process is probably more influenced by the deposition of foreign dust in the topsoil as opposed to the weathering of the soil parent material.

In this study, by comparing the Hequ, Laneika and Langmu regions, I found that the presence or absence of the OA horizon is critical to the pedogenesis process in alpine meadows, the Laneika region has no mattic epipedon, the Langmu region has a low degree of root-mat, while the Hequ region has the most complete OA horizon. the OA horizon increases the soil porosity and CEC content due to the accumulation of large amount of organic matter, the soil weathered layer (solum) in Hequ and Langmu is also thicker than that of Laneika. The climate and vegetation are considered to be the main soil-forming factors in the pedogenesis of phaeozems in Central Europe (Driessen et al., 2001; Wilhelmy, 1950). My study showed that the degree of soil development was highest in Hequ, followed by Laneika and Gongba. Therefore, my study suggests that the main soil-forming factor in alpine meadows is the OA horizon, followed by altitude, time and topography.

### 4.2 Distribution Characteristics of Mattic Epipedon

In this study, I found the OA horizon exist at these five sites, which are HQ1-L, HQ2-M, G-C, G-N and L-H, respectively. I sorted the OA horizon according to their morphological and textural characteristics, with the best root-mat structure at G-C, followed by HQ1-L, HQ2-M, G-N, and L-H. The current geographic distribution of the mattic epipedon is mainly unified with the distribution of *Kobresia* pasture (Miehe et al., 2008). My research has also shown that the formation of the mattic epipedon is dependent on the dense root system of the *Kobresia* and the high altitude and low temperature in alpine environments, hence there is no doubt that *Kobresia* pasture covers the mattic epipedon. However, it is unscientific to equate the distribution of the mattic epipedon with the *Kobresia* pasture, because Laneika is part of *Kobresia* pasture but without the mattic epipedon.

In studies on the north-eastern QTP, the spatial distribution of the mattic epipedon is characterized by high altitude, high precipitation, high vegetation coverage, and near-surface groundwater level (Zhi et al., 2017). In my study, I found that HQ1-L, HQ2-M, G-C, G-N have the most complete root-mat structure and the same topographical characteristics, (1) elevations between 3400 and 3500 meters, (2) flat terrain, sufficient solar radiation, and windy, (3) *Kobresia* is the absolutely dominant species.

I have consolidated the results of the study on the geographical distribution of the mattic epipedon and summarized its main distribution characteristics (Gong and Chen, 1999; Jin et al., 2017; Kaiser et al., 2008; Miehe et al., 2008; Zhi et al., 2017), as follows:

(1) Vegetation; distributed in *Kobresia* pasture, and the degree of development of the mattic epipedon is proportional to the degree of dominance of the *Kobresia*.
(2) Altitude; the degree of development of the mattic epipedon varies at different altitudes, with root coils occurring above 3000m.
(3) Slope; the lower slope leads to a higher degree of development of the mattic epipedon.
(4) Orientation; the mattic epipedon is mainly found on sunny slopes (facing north), and the more northerly the orientation leads to a higher degree of development of the mattic epipedon.

Because of the harsh natural environment of the Tibetan Plateau, fieldwork is complicated and difficult and there is a lack of individual meteorological data for each sample site. Therefore, in the summary above I are unable to give a more detailed description of the distribution characteristics, such as precipitation, temperature, etc.

## 4.3 Formation Processes of Mattic Epipedon

In this study, I found that the mattic epipedon of HQ3-H and G-N was completely destroyed, and the soil surface of G-N had formed a new mattic epipedon about 7 cm thick, whereas the exposed surface of HQ3-H was only covered by blue-green algae and crustose lichens(Unteregelsbacher et al., 2012). HQ2-M is under the dual threat of overgrazing and rodent destruction, and each sample site presents a different state, so my study demonstrates the entire pedogenic process of the mattic epipedon.

The mattic epipedon undergoes the following cycle from intact to destroyed to rebuilt (Fig. 4-1);

- Step 0, due to moderate grazing activity (seasonal migration) and little or no rodent activity, leaving the layer with an intact root-mat structure and high soil fertility (high soil organic matter, CEC, EC, soil moisture) (HQ1-L and G-C);
- Step 1. Due to overgrazing and its indirect triggering of rodent (pika) invasions (Qiao and Duan, 2016), the surface structure of the mattic epipedon is beginning to deteriorate (HQ2-M);
- Step 2. A surge in livestock load per unit area, or human damage, results in a complete destruction of the mattic epipedon, which appears as a crust (HQ3-H).
- Step 3. Grazing bans are initiated and human intervention in the reproduction of rodents. As time passes when plants (*Kobresia*) are re-cover and the root system is gradually deposited downwards, coupled with a short summer growth period with concentrated rainfall and long periods of low winter temperatures, as well as frequent freeze-thaw alternations, the roots become intertwined with the surface soil and a new mattic epipedon begins to rebuild (G-N)

The results of this study show that recovery from damage of the mattic epipedon is possible, but that restoration to its original state takes least 60 years, and furthermore, secondary damage (overgrazing and rodent activity) caused by other factors must be strictly controlled. This process that impedes local livestock production as well as causing incalculable damage to the ecology of the entire Tibetan Plateau. Therefore, a more detailed understanding of the mattic epipedon, including extensive field investigations and analysis of the chemical components of SOM, will provide a crucial contribution to assessing the ecological significance of the mattic epipedon and to understanding the response mechanisms of the QTP to global warming.

### 4.4 Conservation of mattic epipedon

In this study, I reveal the structure of the mattic epipedon at various levels of development, and present the stages of decomposition of plant litter at high altitudes region, my research suggests that the mattic epipedon is a key layer for soil water and nutrient retention, and is the main functional zone of alpine soils on the QTP, and is critical to the pedogenesis process of alpine meadow soils. In my study, the mattic epipedon was re-established after destruction, but in most areas of the QTP, the destruction of the mattic epipedon is irreversible (Miehe and Miehe, 2000).

In the Step 3 of the previous section, the mattic epipedon is expected to recover after the grazing ban and the control of the rodent population, but the degraded grassland will suffer a different situation; The continuous grazing and rodent population outbreaks resulting in extensive burrowing density, resulting in subsurface sand covering the topsoil, combined with the local climate characterized by windy, dry winters and a gradual desertification(Jin et al., 2009; Li et al., 2016; Wang et al., 2000). The chapter 3 suggests that the mattic epipedon is directly related to the degradation of meadow soils, the absence of the mattic epipedon accelerates soil degradation directly. Currently, the restoration of degraded meadows (Black beach) is more towards the restoration after the complete destruction of the mattic epipedon, such as fencing, grazing ban, rodent control, seeding, etc(Fan et al., 2010; Feng et al., 2003; Li et al., 2013a; Zhou et al., 2005).

However, some studies have demonstrated the difficulty of restoring extremely degraded grasslands (Li et al., 2013b), and my study also suggests that the rebuilding of mattic epipedon is least 60 years. Therefore, stages where the mattic epipedon shows signs of destruction, such as reduced vegetation cover and the presence of rodent burrows, while the root-mat structure is still present, for example in the HQ2-M stage. From this stage a series of conservation actions are implemented, including reduction of livestock numbers, seasonal nomadic grazing activities and control of rodent populations, the more advocated method is by increasing the number of small rodent predators (eagles) (Li et al., 2016), which is more conducive to the sustainable development of the QTP ecosystem.

Due to the fragile ecosystem and harsh climatic conditions of QTP, it is extremely difficult to recover from degradation and irreversible damage to the environment. Therefore, it is important to protect the integrity of the mattic epipedon, and to prevent grassland degradation as the main task.

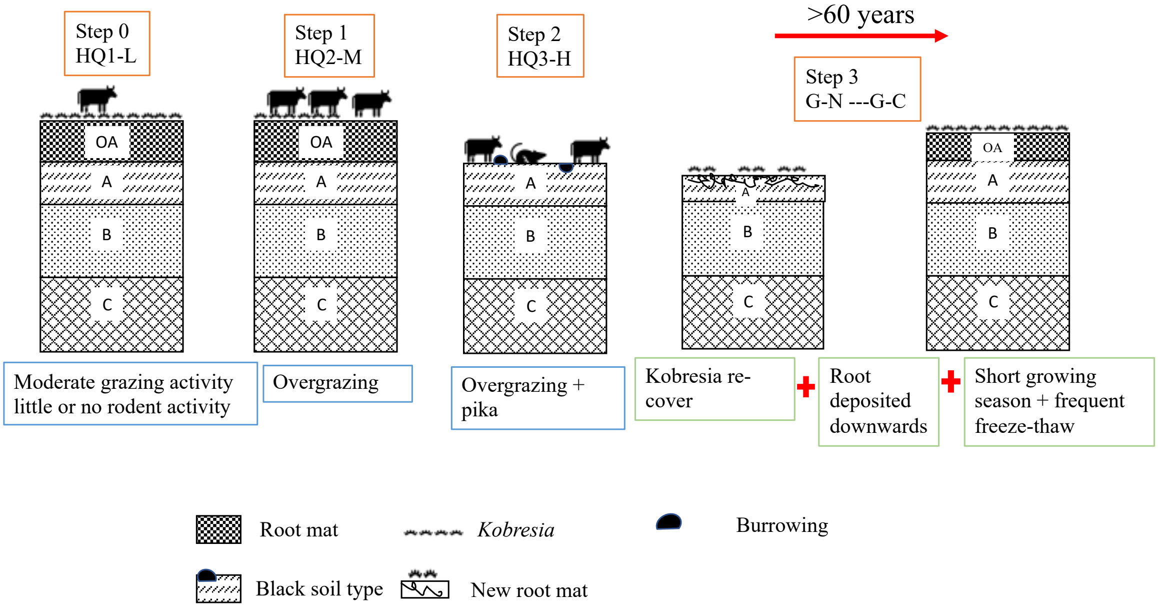


Figure 4- 1 Pedogenesis Processes of OA horizon

# Acknowledgements

My deepest gratitude goes first and foremost to many people in Faculty of Life and Environmental Sciences, University of Tsukuba. Professor Kenji Tamura, his extensive supervision throughout all of time in my study and invaluable supports to me not only in research but also in my life in Japan. Assistant professor Maki Asano, for giving me encourage to do this study and field work, I could not have done this study without her enormous advice. Professor Takashi Kamijo and Professor Mitsuru Hirota, for giving me insight comments.

I would never go so far like this without their endorsement and supervision. I am very grateful to Mr. Hiroaki Shimada, Mr. Zhang Xiulong, Gradute School of Life and Environmental Sciences, for the moral support on my laboratory experiments. I am deeply grateful to Professor Wuyunna, Dalian Nationalities University, for the moral support and warm encouragements during my study.

I gratefully acknowledge the support of president Wang tao, LanZhou Branch Chinese Academy of Sciences and Professor Hou Haisong, Luqu Grassland Research Station, Gansu Province, for their arrangement and assistance in the field research and warm encouragements during my study. would like to thank Mr. Cairangzhaxi, Mr. Xiaoliang Xu and Mr. Jiuxiancairang for extensive support in the fieldwork. I sincerely thank to Mr. Hu Xiaoxing, Gradute School of Life and Environmental Sciences, for kind suggestions on Vegetation Survey and warm encouragements throughout my study.

I also want to thank all laboratory members of Soil Environmental Chemistry, who have been spending many times together and helping each other. Most importantly, I want to express the love and appreciation especially to my family, their encouragement and believing in my skills. Especially, I would like to express the love and appreciation to Ms. Liu Mengyao, for giving me encourage.

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