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Impacts of ecological restoration programs on water-related ecosystem services: A case study in northern Shaanxi, China

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Résumé

Pour restaurer les fonctions écosystémiques altérées, la Chine a instauré plusieurs programmes de restauration écologique (PRE) à grande échelle. Ces programmes ont généré des changements significatifs sur l'occupation du sol et sur les services écosystémiques (SE) définis comme étant les bénéfices procurés aux humains par les écosystèmes. Les écosystèmes sont critiques pour le bien-être humain, mais notre connaissance actuelle de la fourniture des SE dans le paysage contient des lacunes qui limitent notre capacité à mieux comprendre l'impact des PRE sur ce bien-être humain. Plus particulièrement, la compréhension des impacts des changements d'occupation du sol sur la fourniture des SE en régions semi-arides et arides en Chine reste floue.

Dans la présente thèse, le but général de recherche est l'évaluation à long terme de l'impact des PRE sur les SE liés à l'eau, particulièrement l'érosion du sol et l'apport en eau dans une région semi-aride chinoise, le Shaanxi septentrional. Afin d'atteindre cet objectif, les étapes du projet sont: l'analyse des changements d'occupation du sol avant et après l'implantation des PRE, l'estimation de l'érosion du sol et de l'apport en eau à différentes échelles spatiales et temporelles, l'analyse des relations entre le changement d'occupation du sol et les SE liés à l'eau et des relations entre l'érosion du sol et l'apport en eau et finalement l'analyse des impacts potentiels futurs des PRE sur les SE liés à l'eau à l'aide de différents scénarios.

Les résultats ont montré que l'implantation des PRE dans le Shaanxi du nord avait provoqué une augmentation des prairies et des terres boisées et une diminution des terres cultivées. Dans le même temps, la principale caractéristique du changement de SE lié à l'eau au cours de la période d'implantation des ERP était la diminution de l'érosion du sol et de l'apport en eau dans le site d'étude. Cependant, en se basant sur une analyse à l'échelle des sous-bassins versants, il a été constaté que les zones boisées et les prairies n'avait pas augmenté dans tous les sous-bassins au cours de la période d'implantation des ERP. De plus, l'érosion des sols dans trois sous-bassins versants a même augmenté après la mise en œuvre des PRE, alors que l'apport en eau dans tous les sous-bassins versants a diminué durant la même période.

Les relations entre les types d'occupation du sol et les SE liés à l'eau ont varié d'un sous-bassin à l'autre. En ce qui concerne l'érosion du sol, 95% de la zone d'étude a montré une relation positive, indiquant que l'augmentation de la superficie des terres cultivées est liée à une augmentation de l'érosion du sol. En d'autres termes, la diminution des superficies cultivées peut aider à réduire le risque d'érosion des sols. Cependant, les relations négatives observées entre les terres boisées et l'érosion du sol et entre les prairies et l'érosion du sol n'ont été observées que dans la plupart des sous-bassins nord, ce qui suggère que l'augmentation des zones boisées et des prairies dans la plupart des sous-bassins versants du nord peut aider à réduire le risque d'érosion du sol. Ainsi, la mise en œuvre des ERP dans les régions du nord du site d'étude a eu des impacts positifs sur l'érosion des sols. En ce qui concerne l'apport en eau, 65% de la zone d'étude (21 sous-bassins versants) présentaient une relation négative entre les terres boisées et l'apport en eau, tandis que 40% de la zone d'étude (neuf sous-bassins versants) a montré une relation négative entre les prairies et l'apport en eau durant la période d'activité des PRE. Ces résultats indiquent que l'augmentation des terres boisées et des prairies peut diminuer l'apport en eau dans la plupart des sous-bassins versants du nord du Shaanxi. Enfin, il a également été constaté que des compromis existaient entre l'érosion du sol et l'apport en eau, ce qui signifie qu'une amélioration du service de l'érosion est obtenue au prix d'une diminution de l'approvisionnement en eau dans le nord du Shaanxi.

Sur la base de notre analyse de scénarios, les PRE sont susceptibles de continuer à être d'importants et d'influents facteurs sur l'érosion des sols et l'approvisionnement en eau dans le cadre des scénarios de protection et de statu quo. Par rapport à l'année de référence (2015), l'érosion du sol a montré une tendance à la baisse dans les scénarios de protection et de statu quo, mais les résultats de la simulation ont montré des différences relativement faibles dans les deux scénarios. De plus, l'apport en eau parmi trente sous-bassins diminuerait de 28% (scénario sans changement d'occupation du sol), de 29% (scénario de statu quo) et de 37% (scénario de protection). Ces résultats indiquent également que le climat (par exemple les précipitations et l'évapotranspiration), les PRE et leurs interactions exerceront probablement des pressions considérables sur l'approvisionnement en eau d'ici 2050. Ainsi, les pratiques de restauration écologique actuelles pourraient soutenir la conservation des sols et de l'eau dans le nord du Shaanxi.

Mots clés : Programmes de restauration écologiques; érosion du sol; apport en eau; occupation du sol; analyse de scénarios.

Abstract

To repair the damaged ecosystem functions, China has implemented several large-scale ecological restoration programs (ERPs). These programs have exerted significant changes on land use and land cover (LULC) and ecosystem services (ES), benefits that people obtain from ecosystems. Ecosystems are critical to human well-being, but our current knowledge of the provision of ES across landscapes contains gaps that limit our ability to better understand the impact of ERPs on human well-being. In particular, how the changes in LULC affect multiple ES provision in semi-arid and arid regions in China remains unclear.

In this thesis, the overall research goal is to evaluate the impacts of ERPs on water-related ES, namely soil erosion and water yield, in a semiarid region (northern Shaanxi, China), in the long-term period. To attain this goal, the specific steps are: analyse LULC changes before and after implementation of ERPs, estimate soil erosion and water yield at different temporal and spatial scales, assess the relationship between LULC change and water-related ES and the relationship between soil erosion and water yield, and finally, analyse potential impacts of ERPs on water-related ES in the future through different conservation scenarios.

Results showed that the implementation of ERPs in northern Shaanxi caused grasslands and woodlands increase as well as croplands decrease. At the same time, the major characteristic of water-related ES change during the ERPs period was that both soil erosion and water yield decreased in the study site. However, based on sub-watershed scale analysis, it was found that woodland and grassland in each sub-watershed did not always increase during the ERPs period. Moreover, soil erosion in three sub-watersheds actually increased after implementation of the ERPs, while water yield in all sub-watersheds decreased during the ERPs period.

Relationships between LULC types and water-related ES varied from one sub-watershed to another. As for soil erosion, 95% of the study area showed a positive relationship, indicating that higher cropland increase is linked to higher soil erosion increase. In other words, decreasing cropland areas can help reduce the risk of soil erosion. However, the negative relationships between woodlands and soil erosion and between grasslands and soil erosion only existed in most north sub-watersheds, indicating that higher woodland/grassland increase is related to lower soil erosion increase. This result suggested that increased woodlands and grasslands in most north sub-watersheds can help reduce the risk of soil erosion. Thus, implementation of the ERPs in north regions in the study site has positive impacts on soil erosion. As for water yield, 65% of the study area (twenty-one sub-watersheds) showed a negative relationship between woodlands and water yield, while 40% of the study area (nine sub-watersheds) showed a negative relationship between grasslands and water yield after implementation of ERPs. These results indicated that increased of woodland and grassland can decrease water yield in most sub-watersheds in northern Shaanxi. Lastly, it was also found that trade-offs existed between soil erosion and water yield, which means that an improvement in erosion service is achieved at the expense of a decrease in the provision of water in northern Shaanxi.

Based on our scenario analysis, the ERPs are likely to be continued as important and influential on soil erosion and water provision under protection and business-as-usual (BAU) scenarios. Compared with the baseline year (2015), soil erosion showed a decrease tendency under protection and BAU scenarios, but simulation results showed relatively small differences under both scenarios. Moreover, water yield among thirty sub-watersheds would decrease by 28% (No LULC change scenario), 29% (BAU scenario), and 37% (protection scenario). These results also indicate that climate (i.e. precipitation and evapotranspiration), the ERPs and their interactions are likely to place substantial pressures on the provision of water by 2050. Thus, current ecological restoration practices might support soil and water conservation in the future in northern Shaanxi.

Keywords: Ecological restoration programs; soil erosion; water yield; land use and land cover change; scenario analysis.

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Acronyms

AICc	Akaike Information Criterion
AET	Annual actual evapotranspiration
AWC	Available water content
BAU	Business-as-usual
CA	Cellular automata
CanESM2	Second generation Canadian Earth System Model
CMDSS	China Meteorological Data-sharing Service System
DCRES, CAS	Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences
DEM	Digital elevation model
ERPs	Ecological restoration programs
ES	Ecosystem services
ET_0	Reference evapotranspiration
GCM	General circulation model
GDP	Gross domestic product
GGP	Grain for green program
GIS	Geographic Information System
GWR	Geographically weighted regression
LISA	Local indicators of spatial association
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
IPCC	Intergovernmental Panel on Climate Change
Kc	Vegetation evapotranspiration coefficient
LULC	Land use and land cover
MCE	Multiple criteria evaluation
MEA	Millennium Ecosystem Assessment
NCEP	National centre for environmental prediction
NFCP	Natural forest conversion program
NFPP	Natural forest protection program
OLS	Ordinary least squares

PET	Potential evapotranspiration
RCM	Regional climate model
RCPs	Representative Concentration Pathway
RUSLE	Revised universal soil loss equation
SDSM	Statistical downscaling model
SL	Slope length-steepness
SLCP	Sloping land conversion program
USLE	Universal Soil Erosion Equation

Chapter 1 Introduction

1.1 Background

Ecosystem services (ES) are widely defined as ‘‘*the benefits people obtain from ecosystems*’’ (Millennium Ecosystem Assessment (MEA), 2005). Based on this definition, the core purpose of ES approaches is to link ecosystem with human well-being. MEA (2005) classified ES into four categories: provisioning services, regulating services, supporting services, and cultural services. Efforts to develop ES approaches began in the late 1990s (Bingham et al. 1995) but have rapidly increased recently (Bagstad et al., 2013; Crossman et al., 2013). Today, the concept of ES has become an important tool for linking the functioning of ecosystems to human welfare (Fisher et al., 2009; De Groot et al., 2010) and it is a significant research topic with diverse scopes supporting ecosystem management at different spatial and temporal scales (Maes et al., 2012; Boerema et al., 2016).

After Chinese economic reform, the rapid economic growth in China has caused changes in ecosystem structures and processes, which led to the loss of biodiversity and decline in ES (Li 2004). Especially, natural disasters (e.g., flooding and drought) caused by ecosystem degradation and climate change occurred more frequently and these disasters have posed a threat on sustainable socio-economic development in recent decades (Lü et al., 2012; Wei et al., 2015). In response, China has implemented several large geographical scale ecological restoration programs (ERPs) starting in 2000, including the Natural Forest Protection Program (NFPP, also known as the Natural Forest Conversion Program, NFCP), and the Grain for Green Program (GGP, also known as the Sloping Land Conversion Program, SLCP). The NFPP and the GGP are two of the biggest ERPs programs worldwide in terms of their operating geographical scales, amount of public investments, and potential environmental implications (Liu et al., 2008; Yin et al., 2010). In 2011, the central government decided to launch the second phase of the NFPP from 2011 to 2020. By the end of 2015, the central government also announced the extent of the new round of GGP.

Currently, evaluating the ERPs has gained further momentum (Zhang et al., 2000; Xu et al., 2006; Trac et al., 2007; Zhen and Zhang 2011). Different scopes and methods have been widely used to assess the ERPs at different temporal and spatial scales in China, such as integrating remote sensing techniques in landscape planning to assess the dynamic changes in land use patterns of the ERPs (Brandt et al., 2012), using an ecological indicator frameworks (Fu et al., 2011) or the concept of economic valuation (Wang et al., 2007) for assessing ES in support of the ERPs, or integrating socioeconomic sustainability in the ERPs assessments (Deng et al., 2006).

However, there is an ongoing debate about the programs' effectiveness and impacts. As ecological restoration measures can affect entire ecosystems, it is likely that these measures may increase the risk of unwanted negative effects at the same time (Buckley and Crone 2008; Halme et al., 2013). Likewise, the ES frameworks can provide a way forward to balance the various objectives that society has for human-dominated landscapes. As such, incorporation of the ES approaches to policy and conservation efforts was rapidly made in recent years (Tallis et al., 2008). However, to our knowledge to date, there are still a number of gaps in the assessment of the ERPs using ES approaches.

1.2 Current gaps in the ERPs assessment using ES approaches

The following paragraph briefly introduces three currently gaps in the ERPs assessment using the ES approaches. Chapter 2 is providing a systematic review of this aspect.

1.2.1 Impacts of ERPs on water-related ES in arid regions remain unclear

It is well known that these ERPs have generated a positive effect on increasing vegetation cover (Deng et al., 2006; Brandt et al., 2012), vegetation and soil carbon sequestration (Li et al., 2012; Zhang et al., 2010) and net primary production (Su and Fu 2013), decreasing soil erosion (Fu et al., 2011; Lü et al., 2012), improving wildlife habitat (Vina et al., 2007), and maintaining soil fertility (Yang et al., 2012). However, most of ERPs that were implemented in arid and semi-arid regions in China were not tailored to the local hydrological, climate, and landscape conditions (Cao et al., 2011). The consequence of such afforestation on water resource remain unclear, and some researchers have expressed doubt whether potential water-related ES can be achieved by China's ERPs in these regions (Cao 2008; Xu 2011; Lü et al., 2012). The vegetation's potential growth capacity in arid and semi-arid regions is limited by the amount of precipitation (Cao et al., 2010). Water is one of the most important factors for large-scale afforestation in these regions (Cao 2008). For example, massive planted trees in the semi-arid Loess Plateau in China altered hydrologic cycles and caused the death of native plants (Cao 2009). In these regions, water availability appears to be unsuitable for afforestation using current tree species, because these trees commonly consumed huge volumes of water compared with native grassland and plants (Feng et al., 2012). Thus, the implementation of ERPs in these regions might become unstable and actually degrade ecological functions.

1.2.2 The relationships among ES need a deeper understanding

To maximize the benefits from the ERPs while maintaining the ecosystem's health, the interaction among ES should be understood. These relationships among ES boil down to trade-off and synergy across spatiotemporal scales (Rodrigue et al., 2006; Bennett et al., 2009). Trade-offs occur wherein the provision of one service improvement while other declines, while synergies occur wherein the provision of one service increases or decreases while another also increases or decreases. If we know that a trade-off between two services is caused by the ERPs and that there is no true interaction among the services involved, then the program improvement can address its effects on one or both services. If, on the other hand, the negative trade-off is initiated by the effect of the ERPs, but enhanced by a true interaction between the services, then simply managing the ERPs is unlikely to truly minimize the negative trade-off in the long-term. Thus, a deeper understanding of the interactions among ES and the mechanism behind these relationships could help improve the programs' effectiveness. However, based on our review in Chapter 2, 85% of studies only evaluated the impacts of ERPs on single ES. Only 6% of studies estimated the impacts of ERPs on two types of ES, while 9% of studies assessed the impacts of ERPs on multiple ES (three and more types of ES).

1.2.3 The needs to establish long-term programs' assessment

It is necessary to establish a temporal scope for the programs' assessment on ES changes that cover the past, present, and reasonably foreseeable future. There is a time-lag effect of implementation of the program and it would take years to be 'seen' in the landscape. Many ecological processes occur over relatively middle or long-term periods. Likewise, the complexity of ecosystems and the various tempo-spatial dimensions have led to the recognition that ecological research must be conducted on middle or long term scales (Lindenmayer et al., 2000). If we just consider short-term program effects on ES changes, maybe the results cannot accurately reflect the trends for the changes of ES. Thus, impacts of the ERPs on ES should be more rigorously evaluated in the long-term period (Liu et al., 2013).

However, based on our reviewed paper in Chapter 2, only 22% of studies analysed more than 30 years temporal extent, while only 7% of studies designed different scenarios to analyse the potential impacts of ERPs on ES in the future. Scenarios are emerging as a powerful tool for exploring uncertain futures in ecological and anthropogenic systems (Sleeter et al., 2012). Scenario analysis can present the opportunities and threats that the future might hold, and then to weight those opportunities and threats carefully when making strategic decisions.

1.3 Research objectives

The overall goal of this study is to analyse the impacts of ERPs on water-related ES, namely soil erosion and water yield, in a semiarid region- northern Shaanxi, China, in the long-term periods. In particular, we seek:

1) **Land use and land cover (LULC) change analysis**: the specific objective is to analyse LULC changes in the temporal and spatial scales, especially focusing on croplands, woodlands, and grasslands, in the study site before and after implementation of the ERPs.
2) **Water-related ES analysis:** the specific objective is to analyse the changes in water-related ES, namely soil erosion and water yield, in the study site before and after implementation of the ERPs.
3) **Relationship analysis:** the specific objective is to analyse the impacts of LULC changes on water-related ES and the relationship between soil erosion and water yield in the study site.
4) **Scenario analysis:** the specific objective is to analyse how to reduce negative impacts of ERPs on water-related ES through designing different LULC change scenarios in the future.

1.4 Research questions, hypothesis, and structure of thesis

This thesis is divided into eight chapters: (Chapter 1) Introduction, (Chapter 2) Literature review, (Chapter 3) Data and methodology, (Chapter 4, 5, 6, and 7) Results, and (Chapter 8) General discussion and conclusions.

Chapter 2 presents the literature review. It answers the following questions:

1) **What is the state of the art in ES assessment research?** Since two seminal publications about ES came out – an edited book by Gretchen Daily (1997) and an

article in Nature on the value of the world's ecosystem services (Costanza et al., 1997), ES literature has increased exponentially. It is important to know what the state of art in ES is during this period: from definitions to classification to valuation, and from integrated modelling to public participation.

2) **How and to what extent have ES approaches been used to assess ERPs in China?** Previous review papers usually focused on the evaluation of environmental and socioeconomic effects of the ERPs rather than on the methods themselves used to assess the ERPs. To our knowledge to date no review studies have provided an overall description of the use of ES approaches to assess ERPs impacts in China.

Chapter 3 presents the data and methodology. The methodological framework focuses on the following aspects: 1) LULC change analysis; 2) water-related ES analysis; 3) relationship analysis; and 4) scenario analysis.

Chapter 4 is analyzing the changes in LULC in northern Shaanxi during the pre-ERPs period (1988-2000) and ERPs period (2000-2015). The research question includes: **How does the ERPs affect LULC changes at different temporal and spatial scales?** Very few of studies quantify how the ERPs affect levels of LULC changes. Thus, this chapter is analyzing LULC changes caused by the ERPs at different temporal and spatial scales.

Chapter 5 is analyzing the changes in water-related ES, namely soil erosion and water yield, in northern Shaanxi in two different time periods. The research question includes: **What is the changes of water-related ES before and after implementation of ERPs at regional and watershed scales?** The management of ES requires scale-appropriate information about the condition, dynamics, and the use of multiple ES (Raudsepp-Hearne and Peterson, 2016). Therefore, this chapter is analyzing water-related ES changes caused by the ERPs at different temporal and spatial scales.

Chapter 6 is analyzing the relationships between LULC changes and water-related ES, and the relationship between soil erosion and water yield. The research questions include:

1) **How have the changes in LULC affected ES provision in a regional scale and watershed scale?** Information on the temporal spatial relationships among LULC types and ES remains limited. Previous studies have explored the impacts of the ERPs or LULC changes on ES at a given scale. At the spatial and temporal scales

and in terms of reversibility, the impacts of the ERPs on ES are complex. Thus, this chapter is firstly analyzing the impacts of the ERPs on ES at multiple scales.

2) **What is the relationship between related ES under the ERPs?** Landscapes differ in their capacities to provide ES and spatial patterns of LULC change can be linked to the capacities of the provision of ES (Burkhard et al., 2009). Thus, appropriate planned and managed land-use can support not only single ES but also other ES. As such, understanding the patterns, interactions, and quantification of multiple ES at landscapes needs to be further examined in order to minimum trade-offs among ES and maintain ecosystem health. This chapter is secondly analyzing the relationship between soil erosion and water yield under the ERPs.

Chapter 7 is analyzing the potential impacts of the ERPs in the future. The research question includes: **How to reduce the negative impacts of the ERPs on water-related ES through scenario analysis?** This chapter is analyzing what level of the ERPs should be maintained in northern Shaanxi through LULC scenario design and integration of climate change.

Chapter 8 presents the general discussion and conclusions. This chapter is to discuss what our results may mean for researchers in the same field and the decision-makers and to state our main conclusions.

Thus, the main hypotheses of this thesis can be formulated as follow:

- ERPs have different effects on soil erosion and water yield.
- ERP effect variations on soil erosion and water yield can be explained by variations in LULC types.
- ERP effect variations on soil erosion and water yield are temporally and spatially scale dependant.

1.5 Research originality

This thesis systematically evaluated the long-term impact of the ERPs on soil erosion and water yield at regional and watershed scales in a semi-arid region in China. The main originality of this thesis includes:

- The overall description of the use of ES approaches to assess ERPs impacts in China.
- The study of the ERP impacts on water-related ES at both regional and watershed scales.

- A long-term ERP impacts evaluation on water-related ES, which covered past, present and scenario analyses in the future.
- An optimized methodology framework to represent effects of the ERPs on water-related ES in a semi-arid region.

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Chapter 2 Literature review

Summary

This chapter answers the following questions: 1) what is the state of the art in ES assessment research? And 2) how and to what extent have ES approaches been used to assess ERPs in China?

The results highlighted three aspects:

1) Current ERP assessment studies don't cover all ES categories equally. Most papers also consider only one ES evaluation;
2) ES approaches have been used to evaluate ERPs at different spatial and temporal scales in China. The regional scale and short-term assessments dominated the reviewed papers. A few of them evaluated the impacts of ERPs on ES at multiple spatial scales;
3) The majority of datasets used were obtained from the global and national databases. Proxy models were the most commonly used models to assess the impact of ERPs on ES. However, 40% of the studies did not report model output validation.

Résumé

Ce chapitre répond aux questions suivantes : 1) quel est l'état de l'art dans la recherche sur l'évaluation des SE? et 2) comment et dans quelle mesure les approches par SE ont-elles été utilisées pour évaluer les PRE en Chine?

Les résultats ont mis en évidence trois aspects :

1) Les études actuelles d'évaluation des PRE ne couvrent pas toutes les catégories de SE de manière égale. La plupart des articles ne considèrent qu'un seul SE dans leur évaluation;
2) Les approches par SE ont été utilisées pour évaluer les PRE à différentes échelles spatiales et temporelles en Chine. L'échelle régionale et les évaluations à court terme dominent les articles examinés. Quelques-uns d'entre eux ont évalué les impacts des PRE sur les SE à plusieurs échelles spatiales;
3) La majorité des données utilisées proviennent de bases de données mondiales et nationales. Les modèles basés sur des proxys étaient les modèles les plus

couramment utilisés pour évaluer l'impact des PRE sur les SE. Cependant, 40% des études n'ont pas rapporté de validation des sorties de modèle.

2.1 A review of ecosystem service approach

2.1.1 Ecosystem services: definitions and classifications

The concept of ES was first introduced in the 1960s by King (1966) and Helliwell (1969) who referred to nature's functions in serving human societies. Since then, ES has gained further momentum (Daily, 1997; Costanza et al., 1997; de Groot et al., 2002). Especially since the release of the MEA (2005), ES literature has increased exponentially (Fisher et al., 2009). However, there is still much uncertainty over the precise understanding of what is meant by ES, and the related terms such as, '*classification*', '*benefits*' and '*values*', which are often used with different meanings from one study to another (Wallace, 2007).

According to Costanza et al. (1997), ES is referred to as *'natural capital'* in which a stock of materials or energy from natural capital yields a flow of ES over time. Fisher et al. (2009) suggest that ES is "*the aspects of the ecosystem, utilized to produce human well-being*". The most widely used definition of ES is defined as "*the benefits people obtain from natural ecosystems*" (MEA, 2005). MEA (2005) classifies ES into four categories: provisioning services, regulating services, supporting services, and cultural services (Table 2-1). Regulating services help to maintain the regulation of ecosystem processes, such as gas regulation. Provisioning services are the products people obtain from ecosystems, such as food. Supporting services are those that are necessary for the production of all other ES, such as nutrient cycling. Cultural services are the nonmaterial benefits people obtain from ecosystems through recreation and aesthetic experiences (MEA, 2005).

Table 2- 1 Ecosystem services and their functions as presented in MEA (2005)

	ES	Brief description	Examples
Regulating services	Climate regulation	Influence temperature, wind, radiation, and precipitation	Greenhouse gas balance
	Gas regulation	Regulation of atmospheric chemical composition	CO_2 emission and sequestration
	Water regulation	Regulation of hydrological flows	Regulating number of floods
	Sediment retention	Retention of soil within an ecosystem	Regulation of soil erosion
	Water purification and waste treatment	Role of biota and abiotic processes in removal of organic matter, axenic nutrients, and compounds	Pollutants such as metals and sediment are processed and filtered out as water moves
Provisioning services	Food production	Conversion of solar energy into edible plants and animals	Crop production
	Raw materials	Conversion of solar energy into biomass for human construction and other uses	Providing timber and fuel
	Water supply	Storage and retention of water	Provision of water
	Refugia	Habitat for resident and transient populations	Providing living space to plants and animals
	Genetic materials	Presence of species with useful genetic material	Providing medicine and materials for science

Supporting services	Nutrient cycling	Storage, internal cycling, processing and acquisition of nutrients	Nitrogen, sulfur and other elemental or nutrient cycles
	Soil formation	Soil formation process	Provision of a medium for production of crops
Cultural services	Recreation	Provide venue for recreation activities	Providing ecotourism activities (e.g. hiking)
	Aesthetic information	Provide scenery and landscape for human enjoyment.	Natural parks
	Science and education	Provide sense of continuity and place	Number of people attach scientific significance to ecosystem

2.1.2 Valuing ecosystem services

ES assessments aim at a quantification of the goods and services provided by ecosystems to human beings, or alternatively losses related to the damage of ecosystems (Costanza et al., 1997). Generally, ES assessments are divided into two categories: the economic assessment of the value per unit of ES and the ecological assessment of ES supply (de Groot et al., 2012). The ecological valuation encompasses the healthy state of the ecosystem measured with ecological indicators (Muller et al., 2000), while economic valuation attempts to measure diverse benefits and costs associated with ecosystems in monetary units (Farner et al., 2002).

Generally, economic valuation methods are divided into two main categories: market-based methodology and non-market based methodology. The market price method is commonly used for estimating the economic value of ES which is bought and sold in commercial markets, such as timber and wood fuel (Hayha and Franzese 2014). However, the true economic value of goods or services may not be fully reflected in market transactions due to market imperfections. Cost-benefit analysis is used specifically for evaluating the economic efficiency of alternative policies that affect ES, and to guide the selection of projects that deliver maximum net benefits from these services to society (Daily et al., 2009). Replacement cost and avoidance cost methods are commonly used for cost-benefit analysis. The replacement cost method is to evaluate in terms of what it would cost to replace that service, while the avoidance cost method is to evaluate on the basis of costs avoided.

Otherwise, economists have exploited a range of techniques to capture the benefits of non-market ES, broadly categorized as revealed and stated preference methods. Revealed preference methods are based on observations of actual behavior and allow making inferences about how individuals value changes in environmental quality. For example, the travel cost method is used to estimate the value of recreational benefits generated by ecosystems. The basic premise of this method is that the time and travel cost expenses that people incur to visit a site represent the price of access to the site. Thus, peoples' willingness to pay to visit the site can be estimated based on the number of trips that people make at different travel costs. Stated preference methods create a hypothetical market for environmental goods or services using a questionnaire or interview and ask respondents to state preferences for bundles of these goods or services. For example, the contingent valuation method is used for obtaining individuals' preferences in monetary terms, for changes in the quantity or quality of nonmarket environmental resources (Birol et al., 2006).

Other studies have focused on using ecological indicators and other ecologically oriented metrics and models to express a unit value from a particular service. As several ES are difficult to directly quantify, most assessments are based on indicator calculations to capture the changes in different ES. Indicators are often referred to as parameters, variables, or proxies that provide aggregated information on certain phenomena (Burger 2006). Niemi and McDonald (2004) defined ecological indicators as "*measurable characteristics of the structure, composition, or function of ecological systems*". These indicators can help to better understand complex realities (Kandziora et al., 2013). They also can present the provision of ES and how they are changing over time and space (Muller and Burkhard 2012).

Studies that used ecological indicators for ES assessments have been applied to many case studies. In particular, potential crop production (Glavan et al., 2015), timber production (Temperli et al., 2013), and the annual average quantity of water produced by a watershed (Notter et al., 2012) are commonly used for assessing provisioning services. For assessing climate regulation, the most common approach is to quantify the terrestrial carbon stocks in the soil and vegetation system. Soil erosion is a commonly used indicator for mapping sediment retention (Nelson et al., 2009). For water regulation, services provided include the maintenance of natural irrigation and drainage, the buffering of extreme river discharges, and the regulation of channel flows (McVicar et al., 2007).

2.2 Overview of the major ecological restoration programs in China

The NFPP, which covered 18 provinces in the upper reaches of the Yangtze River and the upper and middle reaches of the Yellow River, was officially launched in 2000 (Figure 2-1 and Table 2-2). The NFPP aimed to (i) conserve and restore natural forests in the damaged regions; (ii) plant forests for soil and water protection; (iii) reduce timber harvest in natural forests from 32 million m^3 in 1997 to 12 million m^3 in 2003; and (iv) increase 19% forest cover by 2010 (Li, 2004). In 2011, China decided to launch the second phase of the NFPP with a program period of 10 years from 2011 to 2020. The central government plans to cumulatively invest 244.02 billion Yuan (US$39.13 billion) during the second phase, which is to be used mainly for poverty reduction and forest protection. For the second phase, the NFPP aims to increase forest cover by 5.2 million ha, capture 416 million tonnes of carbon, provide 648,500 forestry jobs, further reduce soil erosion, and enhance biodiversity (Liu et al., 2013).

Although the NFPP is important to reduce soil erosion, another important driving force behind soil erosion is farming on sloping lands. Thus, in order to converse sloping farmland, the Chinese government implemented the GGP in 2000 after following successful pilots in Sichuan, Shaanxi, and Gansu Provinces during 1998 and1999. Now, the GGP covered 25 Provinces in large parts of the upper Yellow and the Yangtze River basins where are generally suffered from soil erosion condition and desertification (Figure 2-1). The GGP addresses both environmental and rural economic concerns (Table 2-2). The main task was to retire and converse vegetative cover by 32 million ha by 2010, with 14.67 million ha of cropland to forests and 17.33 million ha through afforesting barren land and mountain closure. After implementing this program in 2000, the GGP has cumulatively increased forest cover by 26.85 million ha, with 9.06 million ha of cropland being converted to forest and grassland, 15.33 million ha barren land being afforested, and 2.46 million ha of forest regeneration by the end of 2011 (SFA, 2012). The auxiliary goal aimed to develop rural economies and to alleviate poverty in the implemented areas. The program is oriented toward restructuring rural economies so that participating farmers can gradually shift into more environmentally and economically sustainable activities such as off-farm work. Thus, the central government announced the new round of GGP at the end of 2015.

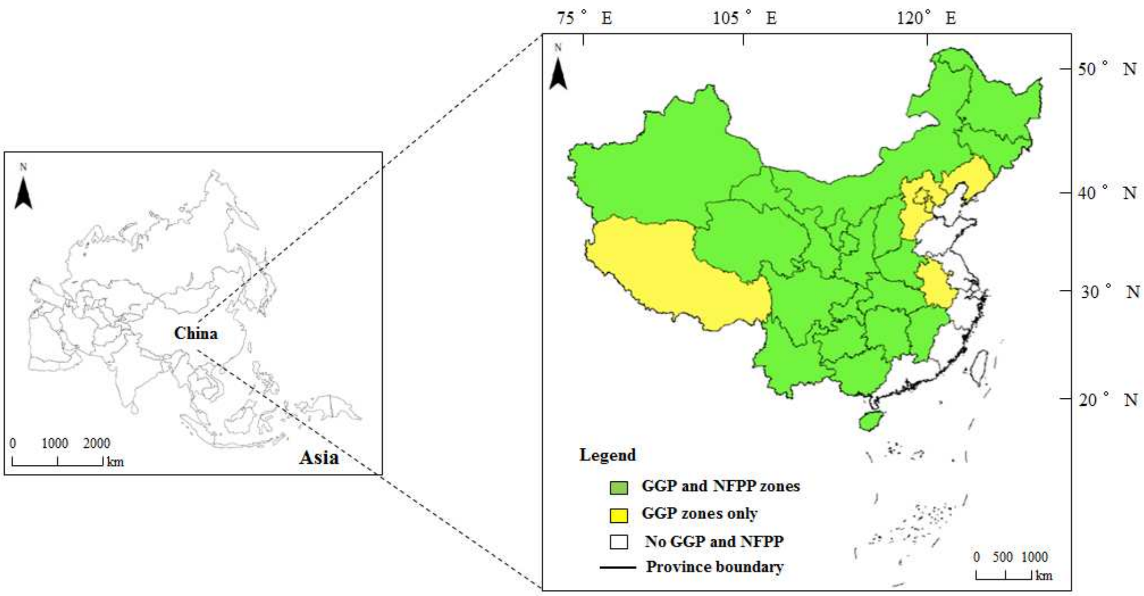

Figure 2- 1 Spatial distribution of the ecological restoration programs at the provincial level, adapted from Liu et al. (2013)

Table 2- 2 Summary of the NFPP and the GGP

The Natural Forest Protection Program (NFPP)	
Payments	$164.86billion
Key policies	• Provide subsidy for forest enterprises and forest workers: Mountain closure to receive a subsidy of $152.35 per ha Aerial seeding to receive $108.82 per ha; • Forest protection to receive $1451 per worker for 340 ha; • Artificial planting to receive $435.3 per ha in the Yangtze River basin and $652.9 per ha in the Yellow River basin.
The Grain for Green Program (GGP)	

Payments	$319.07billion
Key policies	• Croplands on slope more than 25 degrees is converted into ecological forests (e.g. timber-producing forests) and grassland, whereas croplands on the slope between 15 and 25 degrees is converted into economic forests (e.g. fruit orchards) or grassland. • Farmers are supposed to receive compensation such as cash and grains: 2250 kg/ha of grain is subsidized annually for converted croplands in the Yangtze River basin and southern regions; 1500 kg/ha of grain is subsidized annually for converted croplands in the Yellow River basin and northern regions; • $43.53 per ha is provided for living expenses every year and $108.83 per ha is provided for seeds in the first year.

2.3 Review of Chinese ERPs assessment using ecosystem service approaches

This systematic review examined the use of ES approaches to assess two major ERPs: the NFPP and the GGP, both conducted in China. The key question addressed in this section is: how and to what extent have ES approaches been used to assess ERPs in China? This assessment is based on an analysis framework focused on 3 aspects: (1) the ES analysed in relation to the ERPs, (2) the temporal-spatial scales used, and (3) the data sources and models used in the reviewed papers. Sixty-eight papers were selected according to the review criteria.

2.3.1 Materials and methods

2.3.1.1 Literature review

In order to answer our research question, three specific criteria were defined to select the papers to be reviewed in this study.

Criterion 1: The selection of papers was based on 21 commonly quantified Ess grouped into four categories defined by the Millennium Ecosystem Assessment (MEA 2005). These Ess and related search terms (Table 2-3) were individually combined with the terms “NFPP”, “GGP” (including “NFCP” and “SLCP”) using the ISI Web of Science database. Only the papers published in English between 2000 and 2017 were selected.

Table 2- 3 Ecosystem services as categorized by the MEA (2005) and corresponding to the search terms used in the literature review

Category of ES	Ecosystem service	Related search terms
Regulating services	Air quality regulation	Air quality, sandstorm
	Climate regulation	Carbon sequestration, climate
	Pollination	Palliation
	Erosion regulation	Water and soil erosion
	Water regulation	Water retention, flood prevention
	Water purification	Water quality, waste water treatment
Provisioning services	Food production	Crop production
	Fresh water production	Water quantity, runoff, water yield
	Fibre and timber	N/A
	Genetic resources	Genetic
	Biochemicals	Medicinal resources
	Ornamental resources	N/A
Supporting services	Nutrient cycling	N/A
	Primary production	Net primary production
	Soil formation	Soil quality, soil moisture, microbial processes
Cultural Services	Aesthetic values	Aesthetic and education information
	Cultural diversity	
	Educational values	
	Knowledge systems	
	Recreation and ecotourism	Recreation and tourism
	Spiritual and religious values	Spiritual experience

Criterion 2: All the papers needed to assess the ERPs using ES approaches at the landscape scale. In general, ES supplies are temporally and spatially explicit (Fisher et al., 2009). Landscapes play an important role in ES because they contain many important functions which provide several ES to society (De Groot et al., 2010). A better understanding of where, when, and what types of ES are provided by certain pieces of land

can improve landscape planning and program efficiency. Thus, studies that did not analyse ES changes at this scale were out of scope and therefore not further considered.

Criterion 3: The assessment of ES is generally divided into two categories: the economic assessment of the value per unit of and the ecological assessment of the ES supply (De Groot et al., 2012). The ecological valuation encompasses the health state of the ecosystem (Muller et al., 2000), while the economic valuation attempts to measure diverse benefits and costs associated with ecosystems in monetary units (Farber et al., 2002). Since these two categories include numerous and distinct methodological approaches, this review excluded papers presenting economic valuation of ES to focus only on ecological assessment of ES. Based on these three criteria, 68 papers were selected.

2.3.1.2 Assessment framework

Three aspects of the reviewed papers were analysed to study how and to what extent ES approaches were applied to assess the ERPs:

1. ES analysis in relation to the ERPs

   It is acknowledged in the literature that ERPs induced changes on many ES (Liu et al., 2008; Liu et al., 2013). Some papers analysed the impacts of the ERPs on a single service, while others analysed the impacts of ERPs on multiple ES (two and more types of ES). Ecological restoration is a complex process, which involves multiple interactions between the structure, function and composition of ecosystems. That is why the analysis of multiple ES is critical to better understand an ERP's efficiency, and the number of ES analysed and their relationship with the assessed ERPs was systematically reported in the reviewed papers.

To maximize the benefits from the ERPs while maintaining the ecosystem's health, the interactions between ES should be understood. These relationships between ES boil down to tradeoffs and synergies across spatial and temporal scales (Rodríguez et al., 2006; Bennett et al., 2009). Tradeoffs occur when for one service improved, another declines. Synergies occur when for one service that is improved or decreased, another is also improved or decreased. Thus, the amount of ES analysed and the presence or absence of relationship analysis between these ES was systematically reported in the reviewed papers.

2. Spatial and temporal distribution of the studies

The papers were reviewed based on the resolution at which the spatial and temporal results were presented. As for spatial scales, a categorization system was used as follows: 1) the county level assessment refers to the evaluation of ERPs in a specific county, 2) the regional level assessment refers to watershed or catchment, and provincial scales, and 3) the national level assessment refers to the assessment of ERPs across China.

Since GGP and NFPP were officially launched in 2000, many papers analysed the temporal changes in ES before and after the programs, while others only analysed the temporal changes in ES after the implementation of these programs. We defined two temporal categories: historical and scenario. As for the period covered, two classes were defined: the short-term evaluation, which refers to studies covering less than 30 years, and long-term evaluation, which refers to studies covering more than 30 years. Scenarios are usually defined as possible future representations of one or more components of a system. In this paper, scenario analysis refers to the analysis of potential future impacts of ERPs. It should be noted that papers which first estimated the impacts of ERPs on ES during past and present periods before simulating the impacts and potential future impacts of ERPs on ES under different scenarios were categorized as "scenario" papers, because the major research objective in these papers was to analyse the potential impacts of ERPs in the future under different scenarios.

3. ES data and models used to assess the ERPs

The quantifying and mapping of ES largely relied on existing data, which limited the nature of the ES that could be mapped (Naidoo et al., 2008). Some types of data often rely on government-maintained monitoring infrastructures (e.g. climate data), while other data layers are produced by government agencies (e.g. LULC maps). This may not be available in every region or to every researcher. Thus, the review focused on the types of data used and their level of availability. This element was measured based on the availability of free data at multiple spatial-temporal scales for researchers.

The papers were also reviewed to identify which data and models were used to assess the ERPs. Based on previous reviews on the type of method used to quantify each ES (Andrew, et al., 2015; Malinga et al., 2015), a categorization system using three classes was used: 1) direct mapping methods refer to the use of field observations and laboratory analysis to provide information on ES, 2) process-based models refer to the incorporation of representations of physical processes underpinning the functioning of the ecosystem, and 3) proxy models refer to the use of a set of indicators to map ES. Lastly, based on Rykiel (1996), information about internal correction and the performance of the models was also reviewed.

Although 68 papers were selected in the review, it should be noted that some papers can be counted several times in the same analysis depending on the parameter analysed, i.e. the total number of papers can be larger than 68 in some figures and tables. As an example, a paper analyzing ES in different provinces will be counted in each province covered in the spatial scale analysis.

2.3.2 Results

2.3.2.1 Ecosystem services analysed in relation to ERPs

ES approaches have been widely used to analyse the ecological impact of ERPs in China. However, current ERP assessment studies did not evaluate all ES (Table 2-4). As an example, impacts of ERPs on air quality were not found in the review papers. Moreover, results indicated that the two programs were unevenly assessed. 83% of the reviewed papers used ES approaches to evaluate the ecological impacts of the GGP, while 17% of them used ES approaches to assess the ecological impacts of the NFPP.

Figure 2-2 shows the percentage of each ES category in the assessments of the reviewed papers. 46% of studies evaluated the impact of ERPs on regulation services. In particular, these studies focused on evaluating the impacts of ERPs on erosion regulation (e.g. soil erosion) and climate regulation (e.g. carbon sequestration) (Table 2-5). 34% of studies assessed the ecological impacts of ERPs on provisioning services. Specifically, these studies focused on assessing food and fresh water production, fibre and timber, and genetic resources. Only 18% of studies estimated the impacts of ERPs on supporting services, including soil formation and primary production. The reviewed papers showed little interest in evaluating the impacts of ERPs on cultural services, with only 2% of the studies related to these topics. It should be noted that the total number of reviewed papers in Figure 2-2 and Table 2-5 is 89 because some papers were counted several times.

Table 2- 4 Ecosystem services analysed in relation to ecological restoration programs in the reviewed papers

Category of ES	Ecosystem service	Paper analyzing this ES in relation to ERPs
Regulating services	Air quality regulation	No
	Climate regulation	Yes
	Biological control	No
	Erosion regulation	Yes
	Pollination	No
	Water regulation	Yes
	Water purification	No
	Waste treatment	No
Provisioning services	Food production	Yes
	Fresh water production	Yes
	Fibre and timber	Yes
	Genetic resources	Yes
	Biochemicals	No
	Ornamental resources	No
Supporting services	Nutrient cycling	No
	Primary production	Yes
	Soil formation	Yes
Cultural services	Aesthetic values	No
	Cultural diversity	No
	Educational values	No
	Knowledge systems	No
	Recreation and ecotourism	Yes
	Spiritual and religious values	No

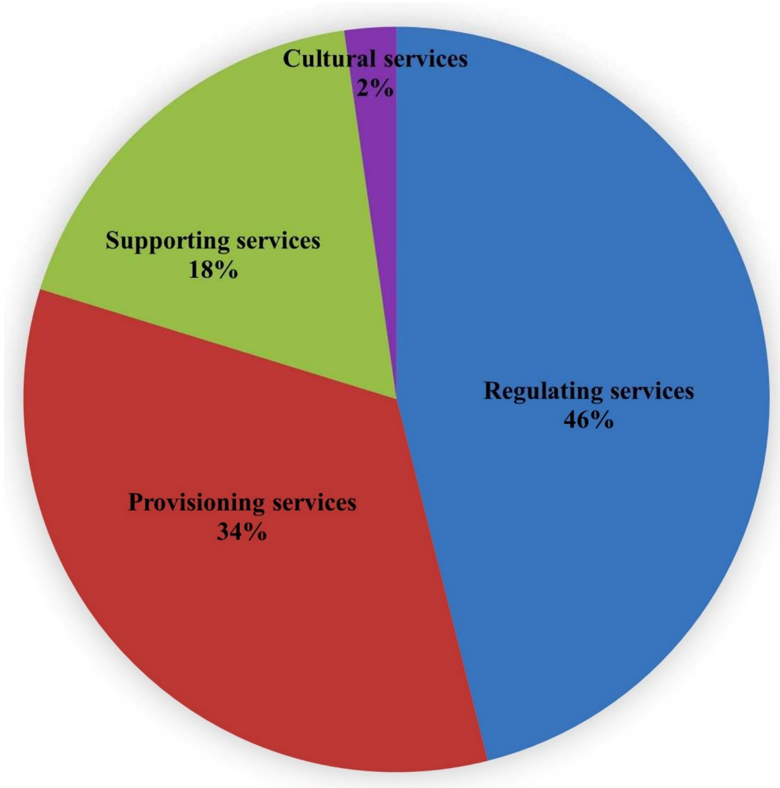

Figure 2- 2 Percentage of each ecosystem service category assessment of the reviewed papers (Total number = 72)

Table 2- 5 Distribution of the reviewed papers for each ecosystem service analysed and each ecological restoration program (total number = 89, papers in bold were counted more than once)

Category of ES	ES	Reviewed papers for the GGP	(%)	Reviewed papers for the NFPP	(%)
Regulating services	Climate regulation	Caldwell et al., 2007 ; Chen et al., 2007a ; Li and Pang 2010 ; Zhang et al., 2010 ; Chang et al., 2011 ; Wang et al., 2011b ; **Lü et al., 2012** ; Wang et al., 2012 ; Wei et al., 2012 ; Deng et al., 2013 ; Song et al., 2014 ; Zhao et al., 2013 ; Zhao et al., 2014 ; Zhou et al., 2014 ; **Chen et al., 2015** ; Zhang et al., 2016 ; He et al., 2016 ; Li et al., 2016	20%	Wu et al., 2011 ; Yu et al., 2014 ; Cao and Chen 2015 ; Jiang et al., 2017	4%
	Erosion regulation	Long et al., 2005 ; Li et al., 2010 ; Fu et al., 2011 ; Gate et al., 2011 ; Xu et al., 2011 ; Deng et al., 2012 ; **Lü et al., 2012** ; **Lu et al., 2013** ; **Su and Fu 2013** ; **Jia et al., 2014** ; Sun et al., 2014 ; **Zhen et al., 2014** ; **Hayashi et**	17%	Liu et al., 2011b ; Guo et al., 2014	2%

		al., 2015 ; Zhang et al., 2015 ; Wang et al., 2017.			
	Water regulation	**McVicar et al., 2007**	1%	**McVicar et al., 2007**	1%
Provisioning services	Food	Feng et al., 2005 ; Deng et al., 2006 ; Deng and Shangguan 2011 ; **Lü et al., 2012** ; Lu et al., 2013 ; Sun et al., 2006a ; Xu et al., 2006 ; Wang et al., 2014b ; Yao and Li 2010 ; **Zhen et al., 2014** ; **Wei et al., 2017**	12%		
	Fresh water	Sun et al., 2006b ; Chen et al., 2007b ; **Zhang et al., 2008** ; Wang et al., 2011a ; Feng et al., 2012 ; Shangguan and Zheng 2010 ; **Lü et al., 2012** ; Cuo et al., 2013 ; **Su and Fu 2013** ; **Jia et al., 2014** ; Wang et al., 2014a ; **Zhen et al., 2014** ; **Hayashi et al., 2015** ; **Wang et al., 2017** ; **Wei et al., 2017**	17%	Zhang et al., 2008	1%
	Fibre and timber			Bu et al., 2008; Zhang and Guan 2007; Konig et al., 2014	3%

Supporting services	Genetic resources	Cleary et al., 2014 ; Liu et al., 2011a ; Zhai et al., 2014 ; **Chen et al., 2015**	4%	Brandt et al., 2015	1%
	Primary production	**Su and Fu 2013** ; **Jia et al., 2014** ; **Yang et al., 2014** ; **Wei et al., 2017** ; **Wang et al., 2017**	6%	Yu et al., 2011 ; **Yang et al., 2014**	2%
	Soil formation	Chen et al., 2008 ; **Li and Pang 2010** ; Yang et al., 2012 ; Zhao et al., 2015	4%		
Cultural services	Recreation and ecotourism	**Brandt et al., 2012**	1%	**Brandt et al., 2012**	1%

ERPs can have an effect on multiple ES, simultaneously or not. However, 85% of studies only evaluated the impacts of ERPs on single ES (Figure 2-3). For example, Wang et al. (2011a) quantified the impacts of ERPs on water yield in northern China. Only 6% of studies estimated the impacts of ERPs on two types of ES, while 9% of studies assessed the impacts of ERPs on multiple ES (three and more types of ES). For instance, Jia et al. (2014) quantified the impacts of ERPs on water yield, soil erosion, and net primary production in northern Shaanxi.

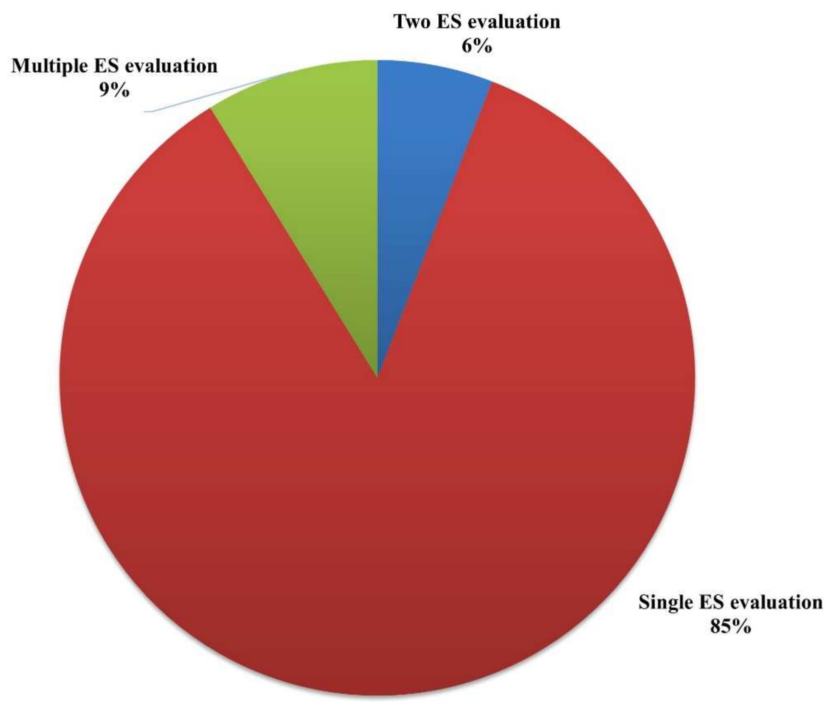

Figure 2- 3 Distribution of reviewed papers according to the number of ecosystem services analysed (total number = 68)

2.3.2.2 Spatial and temporal distribution of the studies

ES approaches were used to evaluate the two ERPs at different spatial and temporal scales in China. However, few of papers evaluated the impacts of ERPs on ES at multiple spatial scales. As shown in Figure 2-4, the regional level assessment dominated the published studies, accounting for 53% of the reviewed papers, followed by county-level assessment, taking up 34% of the reviewed papers. Only 13% of studies considered national scales. Provisioning services (e.g. food production, fibre and timber) were commonly mapped across large areas, while other services were commonly mapped across regional or county scales.

As the NFPP and the GGP almost covered 25 provinces (two thirds of China's territory), we further analysed the spatial coverage of the reviewed papers (Figure 2-5). Thirty papers chose a case study located in Shaanxi Province, while 14 papers chose a case study located in Gansu Province. It should be noted that the total number of papers in Figure 2-5 is 133 because the study sites in several papers covered different provinces. For example, Zhang et al. (2015a) examined the spatial distribution of soil erosion in southern China over 19 provinces.

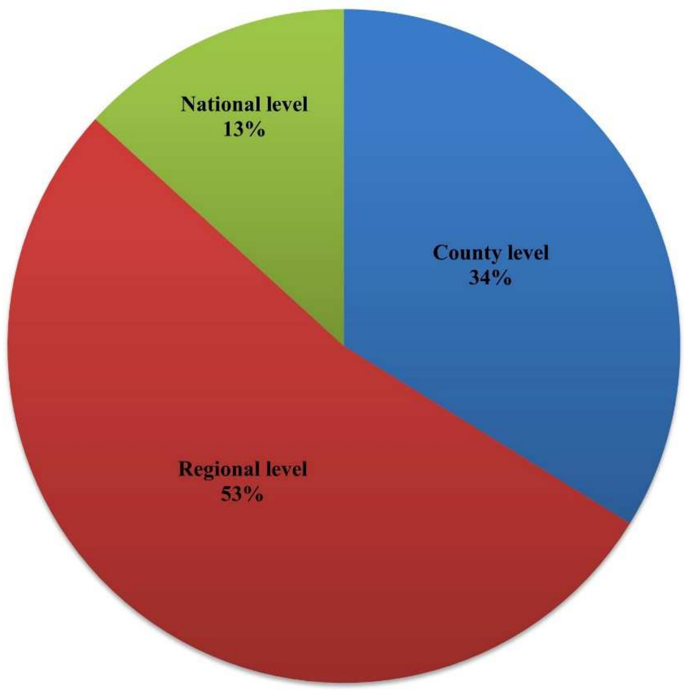

Figure 2- 4 Distribution of the reviewed papers according to the scale of analysis (Total number = 68)

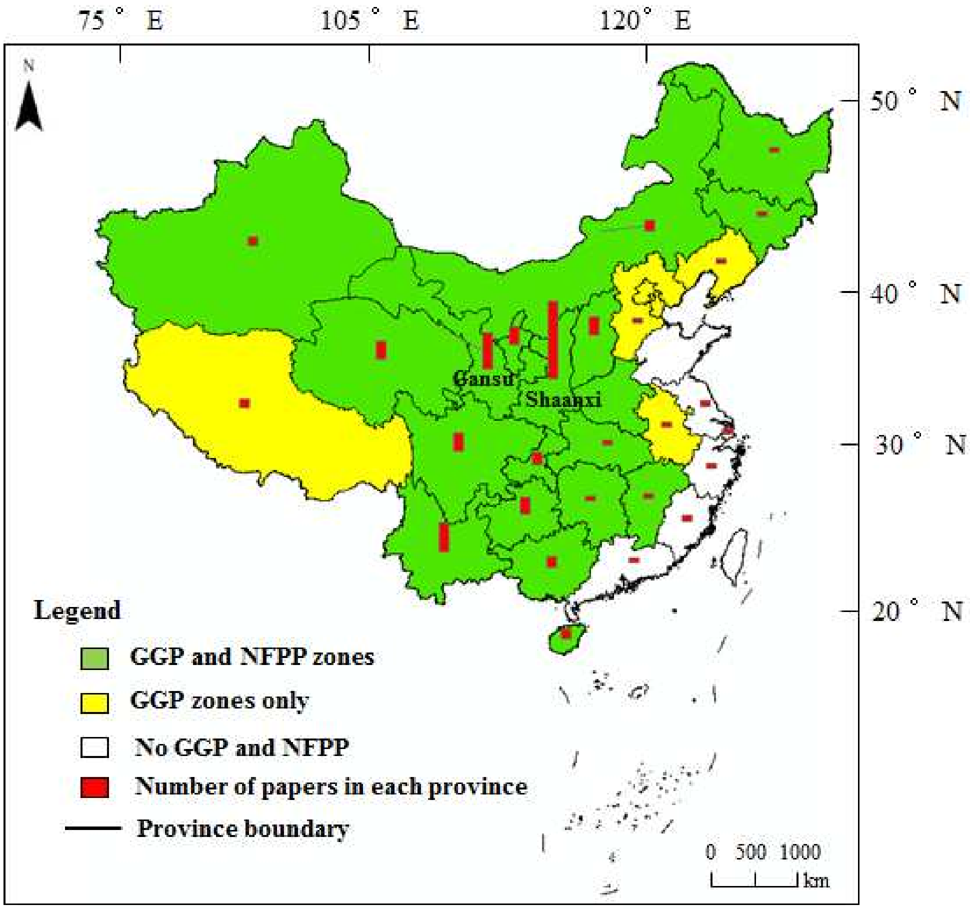

Figure 2- 5 Spatial distribution of the reviewed papers based on the province of their study area in China (total number = 133)

Secondly, our results indicated that temporal scales were unevenly covered by the studies. Based on our results, 71% of studies evaluated the changes in ES related to the ERPs in the short-term (less than 30 years) (Figure 2-6). In particular, most studies focused on evaluating less than 10 years of temporal extent. Only 22% of studies analysed more than 30 years of data, while only 7% of studies designed different scenarios to analyse potential impacts of ERPs on ES in the future. Moreover, scenario analysis focused only on three sub-ES categories: forest products (Zhang and Guan 2007; Koing et al., 2014), crop production (Sun et al., 2006a), and vegetation carbon sequestration (Caldwell et al., 2007).

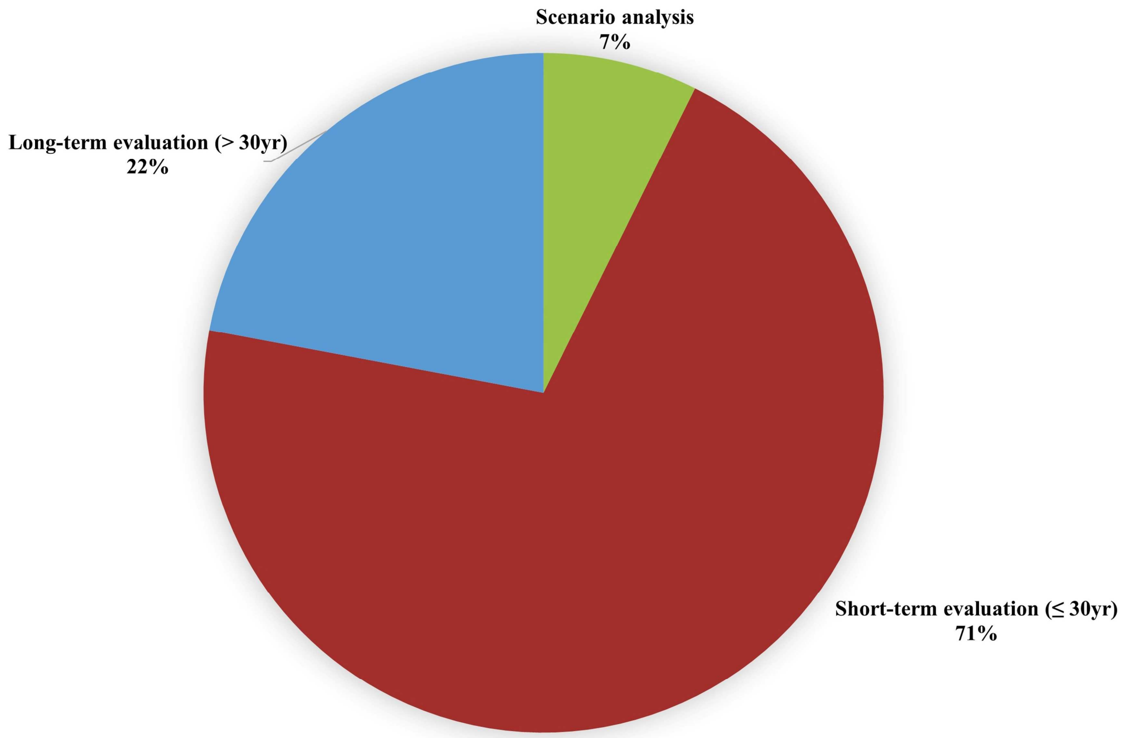

Figure 2- 6 Temporal scale of the reviewed papers (total number = 68)

2.3.2.3 ES data and models used to assess the ERPs

1. Data used to assess the ERPs

Figure 2-7 shows the different data types used to assess the ERPs. The total number of papers in Figure 2-7 is 182 because many papers used more than one type of data. For instance, Feng et al. (2012) examined the effects of the GGP on water yield in the Loess Plateau during 1999-2007. Data used in this paper include climate data (e.g. precipitation and temperature), LULC data (MODIS-ET), and DEM data. 27% of studies considered LULC data as their main source of data. LULC data can be linked to other variables to produce other spatially distributed biophysical parameter values such as water yield, soil erosion, and vegetation carbon dynamic. Topographic data, such as the topographic position, provide information about the elevation of the surface of the Earth, and is usually derived from DEM. In these studies, topographic data provides input to empirical models of water-related services. Likewise, the topographic position (e.g., slope or gully) can affect the intensity of soil erosion and sediment redistribution. The climate regulation service is largely linked to the evaluation of vegetation and soil carbon storage, while the erosion and provision of fresh water services are largely related to local climate and topographic conditions. These services can be indirectly expressed using climate data and soil data. Survey data and statistical data were often linked to LULC data (e.g. Feng et al., 2005) and modelled to estimate the supply of ES.

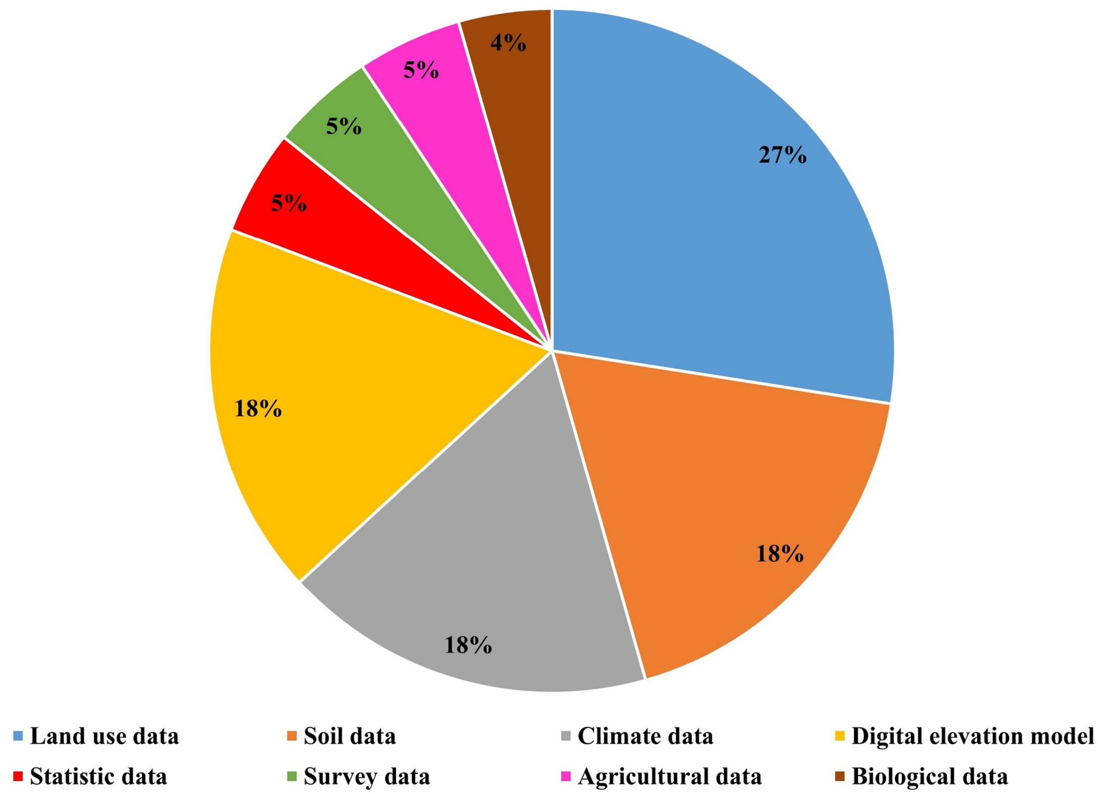

Figure 2- 7 Distribution of data types used in the reviewed papers to analyse ecosystem services (total number = 182)

Secondly, our results indicated that major datasets, including LULC data, DEM, climate data, statistical data, were obtained from global databases or national databases. These databases usually provide multiple temporal-spatial scales and they are also available free of charge to the public. LULC data were mainly obtained from satellite images, such as Landsat and the Moderate Resolution Imaging Spectroradiometer (MODIS) products, as well as aerial photography. Usually, there are no restrictions on Landsat data downloaded from USGS EROS and MODIS Terra+Aqua Combined Land Cover Product downloaded from NASA. DEM data were mainly obtained from the SRTM Digital Elevation Database and the ASTER Global Digital Elevation Model database, which are freely available. Climate data was mainly obtained from the China Meteorological Data-sharing Service System (CMDSS), which includes quality control to provide adequate confidence that an entity will fulfil requirements for quality. Statistical data mainly included socioeconomic variables such as population density and gross domestic product (GDP) and was generally reported by government agencies (e.g. National Bureau of Statistics of China), which are official sources of quantitative ES values information (Konig et al., 2014). These statistical data can be downloaded from the website of the bureau of statistics. However, survey data which was often designed to address specific Ess quantifications were obtained from field sample plots. For example, Chen et al. (2015) examined the changes in soil carbon storage in Hua Jiang Karst Canyon of Guizhou Province. Survey data (e.g. soil samples) were collected from the sampling plots they designed.

2. ES models and tools used to assess the ERPs

In terms of the models and tools used in the ES approach, 65% of reviewed papers used a proxy model to assess the ERPs (Figure 2-8). In particular, as shown in Table 2-6, climate regulating services were usually estimated through quantification of terrestrial carbon stock in the vegetation. Erosion regulation was usually estimated by assessing annual soil erosion rates. The most commonly used models to map soil erosion were the revised universal soil loss equation (RUSLE) and the universal soil loss equation (USLE). Water supply mapping usually estimated the volume of water yield available in a spatial unit. Fibre and timber services were estimated through a quantitative evaluation of harvest timber in a spatial unit. Food production services can be measured with LULC by identifying the net change in potential agricultural productivity. Our results also indicated that the net primary production was the most commonly used indicator to evaluate primary production service.

Moreover, 28% of reviewed papers used direct mapping methods to assess the ERPs. A common characteristic to all soil moisture and soil organic carbon evaluations was the collection of information directly from sample plots. Field observations and laboratory analysis were one of the most commonly used methods in this category, which are essential for determining changes in soil carbon content for different land management treatments at the plot scale. Only 7% of papers used process-based models and the application focused on evaluating soil erosion (e.g. Li et al., 2010) and water regulation (e.g. McVicar et al., 2007).

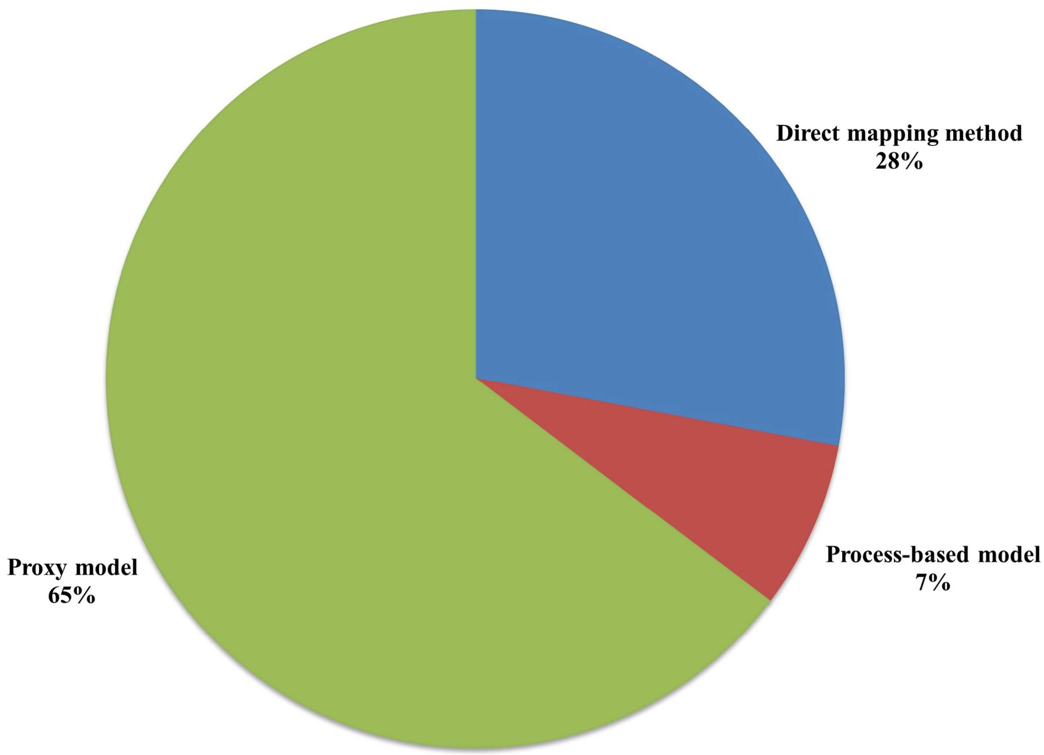

Figure 2- 8 Distribution of the models and tools used to quantify ecosystem services in the reviewed papers (total number = 68)

Table 2- 6 Proxy model examples used in ecosystem services approaches

ES	Proxy	Models and tools	Reference example
Climate regulation	Vegetation carbon	Canonical correspondence analysis	Zhang et al., 2016
		Integrated assessment model	Caldwell et al., 2007
Erosion regulation	Soil erosion	RUSLE	Xu et al., 2011
		USLE	Fu et al., 2011
Food production	Crop production	Agro-ecological zones methodology	Deng et al., 2006

		Agricultural policy simulation and projection model	Xu et al., 2006
Fibre and timber	Timber production	LANDIS model	Bu et al., 2008
		Computable general equilibrium model	Zhang and Gan 2007
Water production	Water yield / runoff / steam flow	Surface energy balance algorithm for land and Thornthwaite's method	Zhang et al., 2008
		Integrated valuation of ecosystem services and tradeoffs model	Su and Fu 2013
		Hydrology-land use model	McVicar et al., 2007
		Water yield response model	Sun et al., 2006b
Primary production	Net primary production	Carnegie–Ames–Stanford approach	Su and Fu 2013

3. ES models testing and analysis

The papers were reviewed based on whether the outputs were validated or not. Forty-one reviewed papers, accounting for 60% of the reviewed papers, validated their outputs. In particular, 19 papers used direct mapping methods, which consist in using survey data obtained from field sample plots (e.g. soil survey samples) and laboratory analysis to provide validation information on ES. Moreover, 22 papers validated their modelling results using observation data which are usually obtained from government-maintained monitoring infrastructures (e.g. weather stations). Among these 22 papers, studies which quantified changes of water yield or runoff usually validated their simulation results. Validation methods included model calibration and comparisons between the simulation results and observation datasets. However, many papers usually used sample data from field experiments to represent changes in their study sites through interpolation or other tools. The validation of simulation results in these papers were essentially partial, although the performance of ES models can be verified by the consistency between observations and calculations. 40% of studies did not report model output validation. For example, the papers using proxy models to assess large-scale impacts of ERPs on ES (e.g. soil erosion) usually did not report a validation procedure, and validation was not common for papers that quantify multiple ES.

2.3.3 Discussion

2.3.3.1 ES analysed in relation to the ERPs

Although ES approaches have been widely used to analyse the ecological impact of ERPs, reviewed ERP assessment studies showed that all ES were not studied. Only a few of papers assessed the impacts of ERPs on supporting and cultural services. Moreover, many studies investigated the impact of ERPs on single ES and only 9% of studies assessed the impact of ERPs on multiple ES or analysed the relationships between multiple ES. The ecosystem should be considered as a whole, because the changes or impacts on one part of an ecosystem can have consequences for the whole system. Bennett et al. (2009) stressed the importance of understanding direct and indirect relationships between multiple ES. From a management perspective, targeting the sustainable development of a single service's supply might have a positive or negative impact on the supply of another ES. These interactions are principally determined by the synergies or tradeoffs between ES (Baral et al., 2014). Landscapes differ in their capacity to provide ES and the spatial patterns of LULC changes can be linked to the provision capacity of ES (Burkhard et al., 2009). Thus, appropriately planned and managed land use, can support not only single ES, but also other ES. As such, the patterns, interactions, and quantification of multiple ES need to be further examined in order to minimize tradeoffs among ES and to maintain ecosystem health.

Likewise, although many studies have already assessed the impact and efficiency of ERPs, ways to enhance the effectiveness of these programs remain unclear. In China, most of the programs were not tailored for the local hydrological, climate, and land conditions of the arid and semi-arid regions covered by the program (Cao et al., 2011). These programs could simultaneously increase the risk of unwanted negative effects. The vegetation's potential growth capacity in arid and semi-arid regions is limited by the amount of precipitation. Water is one of the most important factors for large-scale afforestation in these regions (Cao 2008). Massively planted trees in the semi-arid Loess Plateau in China altered hydrologic cycles and led to negative impacts on native plants (Cao 2009). In these regions, water availability appears to be unsuitable for afforestation using currently used tree species, because they require huge volumes of water compared to native ones (Feng et al., 2012). The central Chinese government has already launched the second phase of the NFPP, from 2011 to 2020, and announced, in the end of 2015, that it will extend the GGP for a new round, which means that billions of dollars will be invested. A deeper understanding of the interactions between multiple ES and the mechanism behind these relationships could help improve the programs' effectiveness.

2.3.3.2 Spatial and temporal distribution of programs evaluation

The NFPP and the GGP almost cover two thirds of the Chinese territory, and most regions covered by the programs are both lagging economically and ecologically fragile (Liu et al., 2008). Our results indicated that the impacts of ERPs on ES have been evaluated at different spatial and temporal scales in China. The study site selection in the reviewed papers were in line with major local ecological characteristics or problems. For example, many papers chose northern Shaanxi Province as the case study site, and the program evaluation in this region usually focused on changes of soil erosion (e.g., Fu et al., 2011), water supply (e.g., Feng et al., 2012), and soil formation (e.g., Yang et al., 2012). This is because this region is mainly located in the Loess Plateau which is well-known for its severe soil erosion in China. The climate is mainly characterized by cold and very dry winters and dry springs and autumns. Thus, afforestation in this region usually lead to water shortage (Cao 2009). Moreover, natural disasters like drought, sandstorms, and landslides in this region are quite frequent.

However, most of the studies investigated the impacts of ERPs on ES at a specific scale such as regional scale and administrative districts, and 71% of studies evaluated the change of ES value caused by the ERPs in a short-term (less than 30 years). An increasing recognition that different processes operate at different scales and cross-scale dynamics should be considered in the study of ecological systems (Agarwal et al., 2002). Some ecological processes are associated with a particular scale, while other processes may occur across multiple scales. Given that ecosystems are complex, single temporal and spatial scale observations may capture, miss, or distort ES interactions (Raudsepp-Hearne and

Peterson, 2016). Likewise, the complexity of ecosystems and the various temporal dimensions have led to the recognition that ecological research must be conducted at middle or long-term scales (Lindenmayer et al., 2000).

The growing body of literature regarding LULC change scenario modelling shows its importance and potential role in providing insight and informing landscape planners and policy makers (Nelson et al., 2009; Swetnam et al., 2011; Estoque and Murayama 2012). However, based on our analysis, only 7% of the reviewed studies evaluated scenarios that could allow for policy evaluations. Thus, it is necessary to establish a temporal scope that covers the past, present, and reasonably foreseeable future for the programs' assessment.

2.3.3.3 ES models and data used to assess the ERPs

Our results indicated that the ES data were usually derived from global or national datasets, which offered a practical and economical approach to perform spatially continuous observations. However, it is difficult to obtain large spatial scale and long-term consecutive temporal scale data. Researchers usually use sample data representing changes in large scales and use interpolation or other statistical tools. For example, large spatial precipitation maps are created using point observations, such as weather stations. However, not all the weather stations under the CMDSS framework broadcast a complete set of data and not all stations broadcast continuously. Moreover, observations at large spatial scales are usually scarce (Martínez-Harms and Balvanera 2012). For example, Landsat images can present an incomplete spatial and temporal coverage due to cloud cover in some images. This can increase uncertainties in large-scale ES modelling (Crossman et al., 2013).

Likewise, using data from different temporal and spatial scale and inconsistent approaches can make comparisons assessment result integration difficult. For example, many studies and government reports have confirmed that the NFPP and the GGP have greatly increased the forest area. However, several studies found no significant change in forest cover in some counties. Moreover, several counties showed a forest cover decline due to touristic development (Yin et al., 2010). 27% of studies considered LULC data as the main source of data. LULC data were mainly derived from remotely sensed data. Since the information contained in a remotely sensed image is strongly dependent on the spatial resolution, and the spatial resolution of an image affects every stage of the image classification process (Ghassemian 2016), the spatial resolution of remotely sensed images directly influences ES simulation results. Given that the evaluation of ES is becoming an important tool to guide decision-making, improving the quality of data and establishing multiple data scales is important in order to be able to provide more accurate information.

An impressive suite of models has already been used to represent and analyse the changes of ES under these two programs, such as direct mapping, ecological process-based models, and proxy models. However, 40% of studies did not report model output validation, which may limit the accuracy and precision of evaluation results. Thus, it is necessary to develop robust approaches to ES modelling and valuation.

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Chapter 3 Methodology and data

Summary

In this chapter, details regarding the study site are first presented, followed by the methodology and data requirements. The methodological framework includes four basic components: 1) LULC change analysis, 2) water-related ES analysis, 3) relationship analysis between ES and LULC change, and 4) scenario analysis.

Résumé

Dans ce chapitre, les détails concernant le site d'étude sont d'abord présentés, suivis de la méthodologie et des besoins en données. Le cadre méthodologique s'articule autour de quatre éléments principaux : 1) l'analyse du changement d'occupation du sol, 2) l'analyse des SE liés à l'eau, 3) l'analyse de relations entre les SE et les changements d'occupation du sol et 4) l'analyse de scénarios.

3.1 Study site

3.1.1 Geographical and geomorphic conditions in the study site

With an area of 80,609 km^2, Northern Shaanxi is located in the middle reaches of the Yellow River in China. The Loess Plateau, which is one of the most severely eroded regions in the world (Fu 1989), covers the northern Shaanxi (Figure 3-1). The main geomorphic landforms on the Loess Plateau are hills and various gullies (Figure 3-2a). The Loess Plateau is filled with loess which is a clastic and predominantly silt-sized sediment that travels easily in the wind (Figure 3-2b). Moreover, the Loess Plateau is one of the birthplaces of the Chinese with an agricultural development history (more than 4000 years). However, geological and geomorphologic characteristics and long-term farming practices, combined with huge population pressures, have led to severe environmental degradation (Chen et al., 1988). In particular, ongoing soil erosion in this region is the main environmental constraint on environmental quality and socioeconomic development (He et al., 2004; Fu et al., 2011). Soil erosion can cause soil deterioration, the decline in land productivity and degradation of streams, lakes, and estuaries with transported sediments and pollutants (Xu et al., 2002). Approximately 90% of the sediment in the Yellow River originates from soil erosion on the Loess Plateau (Tang 2004). Thus, in order to help reduce soil erosion and restore damage ecosystem functions, China officially implemented the NFPP and the GGP in 2000 after following successful pilots in the whole Shaanxi Provinces in 1999.

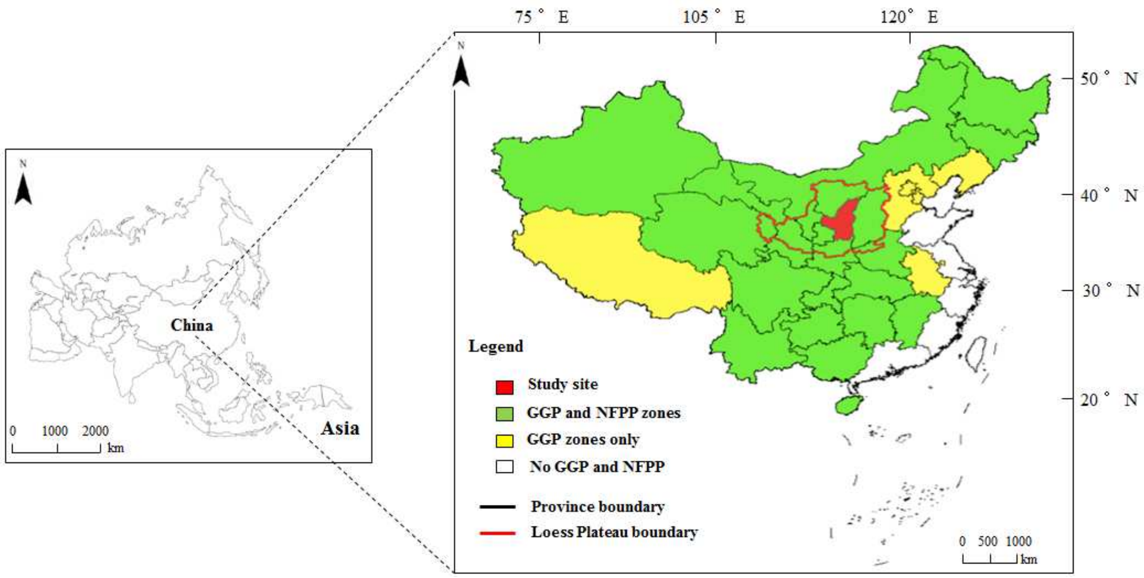


Figure 3- 1 Geographical location of the study area in China

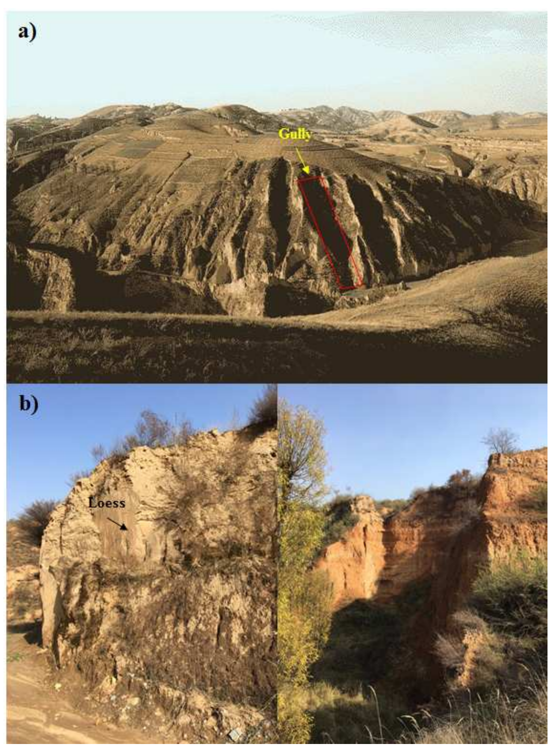


Figure 3- 2 Geomorphic landforms (a) and loess (b) in the Loess Plateau (Northern Shaanxi section- Shenmu county, Yulin prefecture) (photos by Xin Wen)

3.1.2 Climate and vegetation type in the study site

Likewise, northern Shaanxi is also located in the arid and semi-arid regions which are usually characterized by excessive heat and inadequate precipitation. The average annual precipitation during 1951-2010 ranged from 398 mm in the north to 507 mm in the south and most precipitation falls occurred in summer with high intensity rainstorms (Zheng and Sun, 2015). The distributions of average annual precipitation at the study area from 1988 to 2013 is presented in Figure 3-3. During these 25 years, the highest precipitation value was 2013, reached at 624mm, while the lowest precipitation value was 1999, reached at 322mm.

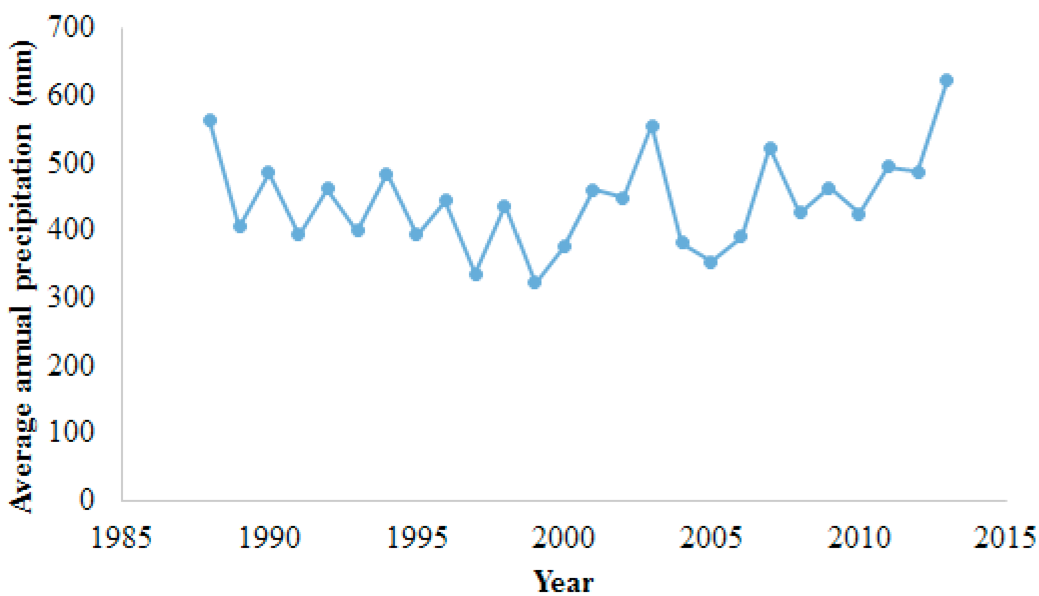
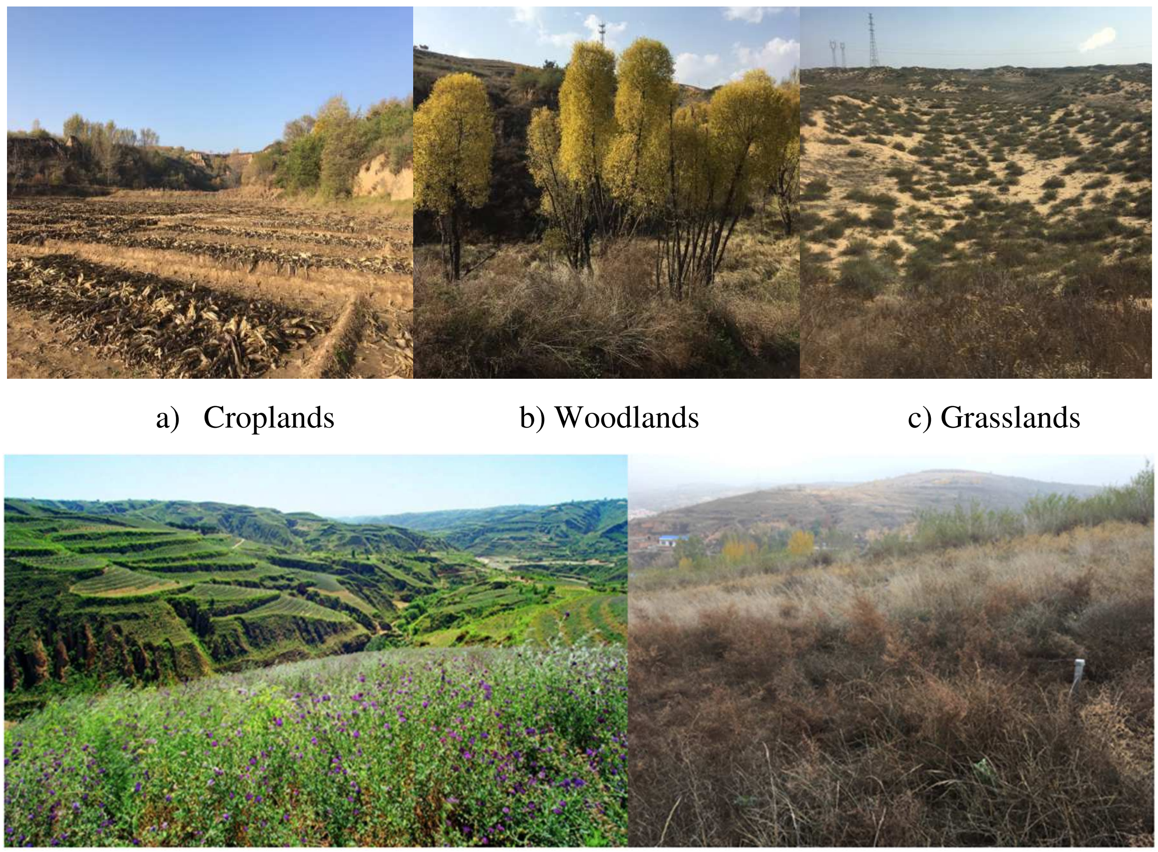


Figure 3- 3 Average annual precipitation from 1988 to 2013 in northern Shaanxi, China

Data source: The China Meteorological Data Sharing Service System

Moreover, LULC types in northern Shaanxi mainly included three types: grasslands, croplands, and woodlands (Figure 3-4a, b, and c). In 2000, the grasslands took up 44% of the total area, followed by the croplands and woodlands, accounted for 36% and 14%, respectively. The grasslands included natural grass, planted grass, and forage crops. However, after implementation of the ERPs in this region, alfalfa (Figure 3-4d) became one of the most widely planted forage crops in northern Shaanxi because it is ideal for conserving soil (Fan et al., 2010). Alfalfa was found to be one of the most intensive water consumption forage crops and one which can severely deplete soil water in the rainfall-limited northern Shaanxi, because alfalfa usually has a high evapotranspiration rate and deep roots that can extract deeper soil water compared with natural grass (Ward et al., 2002; Jiang et al., 2006). Therefore, large-scale converting slope croplands to artificial forestlands and grasslands would greatly influence the hydro-ecological environment in the study site.



a) Croplands b) Woodlands c) Grasslands

d) Alfalfa planted in Shenmu county, Yulin prefecture

Figure 3- 4 Typical LULC types in Shenmu county, Yulin prefecture, northern Shaanxi, (photos by Xin Wen)

3.1.3 Sub-watersheds included in the study site

In this study, the impacts of ERPs on water yield was analysed, which means the impacts assessments should be based on the watershed scales. A watershed is the area of land where all of the water that falls in it and drains off of it goes to a common outlet (e.g. river and bay). Larger watersheds usually contain many sub-watersheds. The watershed connects into other watersheds at lower elevations in a hierarchical pattern, with smaller sub-watershed, which in turn drain into another common outlet. However, it's usually the case that eco-protected area and administrative boundaries do not match watershed boundaries. In this study, due to data limitations, only the area within the administrative boundaries has been modeled. Contribution of water from outside the administrative boundaries was not taken into account. Thirty watersheds were extracted from the DEM data in northern Shaanxi (Figure 3-5). The InVEST water yield model employed to calculate water yield in this study is adapted to the sub-watershed scale of analysis (Mandle et al., 2017).

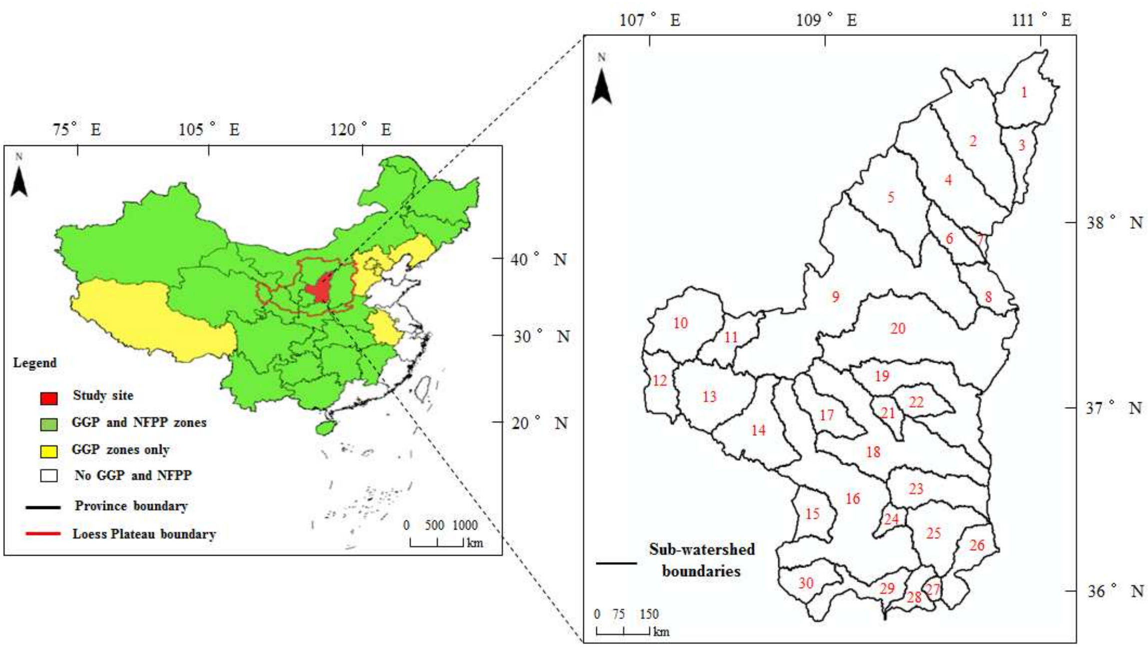


Figure 3- 5 Sub-watersheds included in northern Shaanxi. Sub-watersheds are numbered from 1 to 30.

3.1.4 Social and economic conditions in the study site

Northern Shaanxi, includes Yan'an and Yulin prefectures, covers 25 counties with over 5 million populations by 2015 (Shaanxi statistical yearbook, 2016). As a part of Loess Plateau, there is a long-term agricultural development history. However, economic development in northern Shaanxi has lagged far behind progress on the national average.

The gross domestic product (GDP) in northern Shaanxi was $666[1] billion while the GDP in China in 2013 was $8598 billion, roughly accounted for 1% of the national GDP in 2013 (Shaanxi statistical yearbook 2013; China statistic yearbook 2013). In particular, agriculture, food, and related industries contributed $39 billion to the local GDP, while the manufacturing and industry sector contributed $470 billion to the local GDP, accounted for 71% of the total GDP (Shaanxi statistical yearbook 2013).

3.2 LULC change analysis

Figure 3-6 is the overview of basic methodological steps in this study. The methodological framework includes four basic components:

1) LULC change analysis: quantify the changes of LULC at different temporal and spatial scales before and after implementation the ERPs;
2) Water-related ES analysis: estimate the value of soil erosion and water yield using the Universal Soil Erosion Equation (USLE) and the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model, respectively, and then analyse the changes of water-related ES before and after implementation of the ERPs;
3) Relationship analysis: analyse the effects of LULC changes on water yield and soil erosion using geographically weighted regression (GWR) model, and the relationship between soil erosion and water yield using Pearson correlation;
4) Scenario analysis: design different LULC scenarios and downscale the Representative Concentration Pathway (RCPs) 4.5 scenario to analyse the potential impacts of ERPs on water-related ES in 2050.

[1] 1 Chinese Yuan (RMB) = $0.16 (US Dollar), based on February 2018 currency converter.

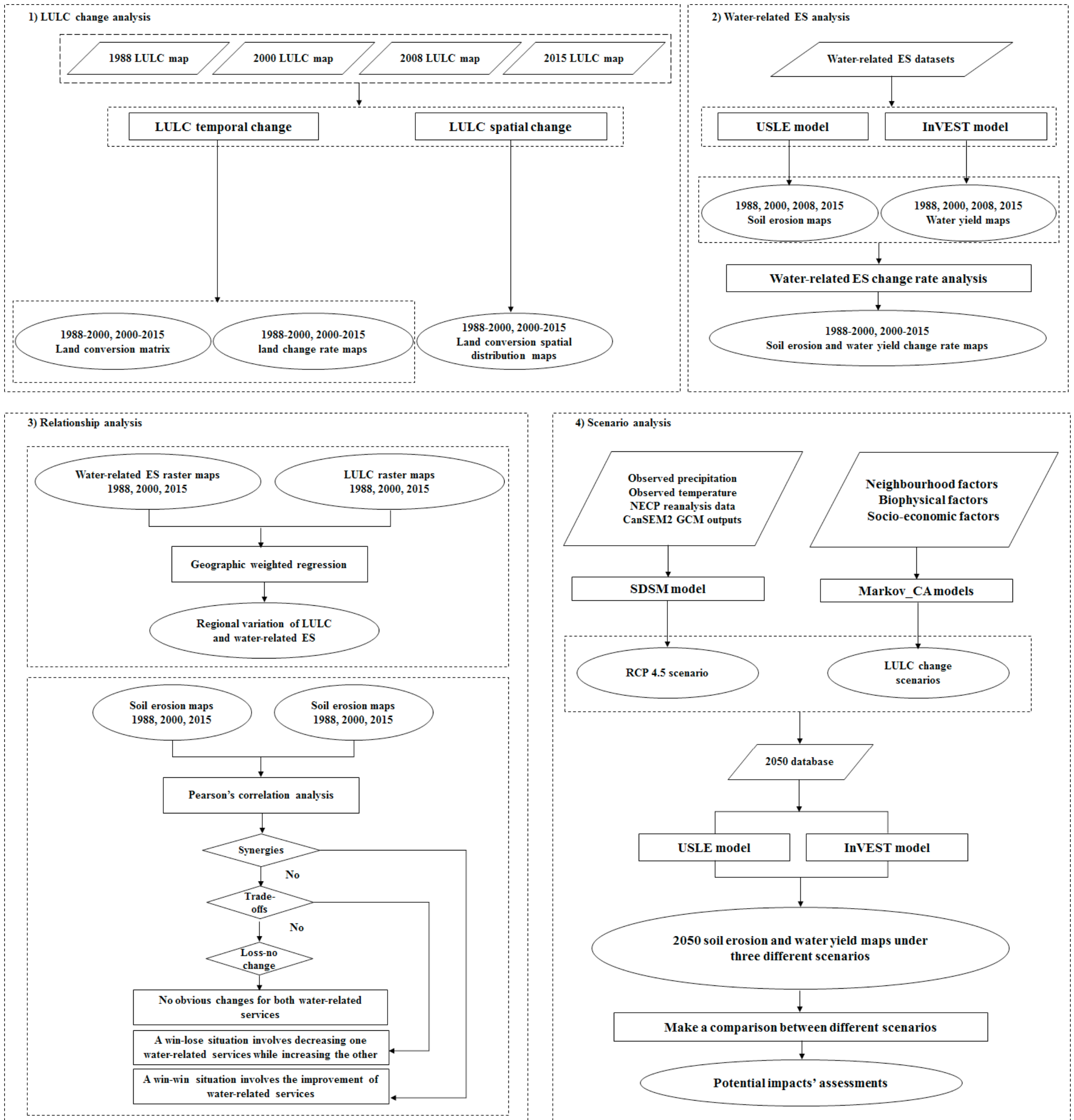


Figure 3- 6 Overview of basic methodological steps in this study

The ERPs aimed to restore the damaged ecosystem functions by converting croplands to forests and grasslands, and afforestation, which caused LULC changes. Thus, we firstly analysed temporal and spatial changes of LULC especially focusing on the changes of croplands, woodlands, and grasslands, in the study site before and after implementation the ERPs. Land conversion matrix was to analyse the area of each LULC class converting to another LULC class based on pre-ERPs period (1988- 2000) and ERPs period (2000- 2015).

Lastly, LULC change rate analysis was to estimate a certain of LULC type increase or decrease from the initial year to the final year by a certain percentage per year.

3.2.1 LULC spatial change analysis

Change detection is the process of identifying differences in the state of an object by detecting it at different time periods (Singh 1989). Timely and accurate change detection of Earth's surface features, e.g. LULC changes, can provide a better understanding of relationships and interactions between human and natural phenomena to better manage and use resources (Lu et al., 2004).

Change maps were produced to analyse patterns of LULC changes over the study area. The post-classification detection method was employed to detect spatial LULC changes in the study site. A pixel-based comparison was used to produce spatial change information on the pixel basis and thus, interpret the total area lost or gained by each LULC class, including croplands, woodlands, and grasslands at two different time periods (Figure 3-7).

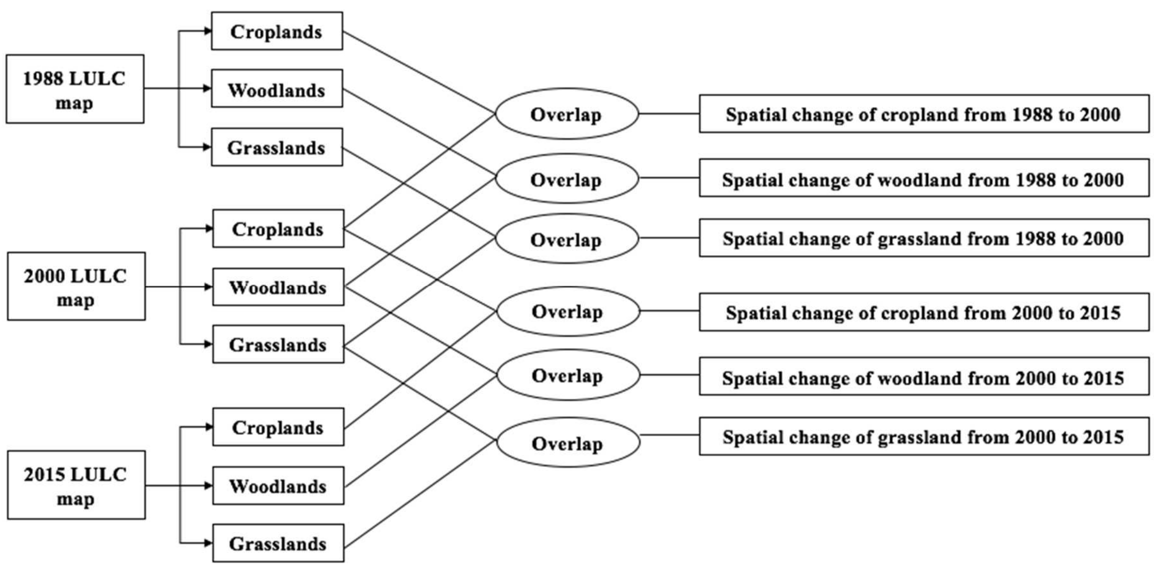


Figure 3- 7 Procedure of LULC change detection in two different time periods

3.2.2 LULC temporal change analysis

The cross-tabulation/matrix was employed to analyse a LULC transition from one class *i* to another class *j* in two different time periods (1988-2000 and 2000-2015). A transition matrix is presented in Table 3-1. Two LULC maps at two moments in time (T and $T_{t+1)}$ are cross-compared (cross-tabulation/matrix). $S_{i,j}$ indicates the land percentage that shifts from one class *i* to another class *j*. $S_{(t+1),\ ij}$ is the total area of a certain LULC type in time T_{t+1}, while $S_{t,ij}$ is the total area of a certain LULC type in time T.

Table 3- 1 Structure of land conversion matrix

		T				
		Class 1	Class 2	…	Class *n*	Total
T_{t+1}	Class 1	$S_{1,1}$	$S_{1,2}$	…	$S_{1,j}$	$S_{(t+1),1}$
	Class 2	$S_{2,1}$	$S_{2,2}$		$S_{2,n}$	$S_{(t+1),2}$
	…	…	…	…	…	…
	Class *n*	$S_{i,1}$	$S_{n,2}$	…	$S_{i,j}$	$S_{(t+1),ij}$
	Total	$S_{t,1}$	$S_{t,2}$	…	$S_{t,ij}$	

In this study, the single land use dynamic index was employed to analyse LULC changes in each sub-watershed. LULC change rate maps were created. The equation can be expressed as follows (Hao et al., 2012):

$$K = \frac{S_{final} - S_{initial}}{S_{initial}} * \frac{1}{T} * 100\% \tag{1}$$

Where K is the annual change rate for a certain LULC type, $S_{initial}$ is the area for a certain LULC type in the initial year, while S_{final} is the area for a certain LULC type in the final year. T is the study period.

3.3 Water-related ecosystem service analysis

3.3.1 Soil erosion quantification

Soil erosion refers to the wearing away of a field's topsoil by the natural physical forces of water or wind. To assess soil erosion risk, one of the most widely used approaches is the USLE, developed by Wischmeier and Smith (1978). The USLE model estimates the annual soil loss per unit area on the base of soil, vegetation and climate conditions, including rainfall erosivity (R, $MJ\ mm\ km^{-2}\ h^{-1}\ yr^{-1}$), soil erodibility ($K$, $t\ km^{2}\ h\ km^{-2}\ MJ^{-1}\ mm^{-1}$), slope length-steepness (SL, dimensionless), vegetation cover management (C, dimensionless) and erosion control practices factor (P, dimensionless). We classify the soil erosion level into 6 class based on the Ministry of Water Resource of the People's Republic of China (1997) (Table 3-2).

The average annual soil loss is a function of five factors described by the expression:

$$A=R*K*SL*C*P \tag{2}$$

where *A* represents the average annual soil loss in ton per square kilometer per year ($t\ km^{-2}\ yr^{-1}$).

Table 3- 2 Guidelines for assessing potential soil erosion level

Erosion level	Average amount of erosion ($t\ km^{-2}\ yr^{-1}$)	Reference
Slight	< 1000	The Ministry of Water Resources of the People's Republic of China (1997)
Light	1000 – 2500	
Moderate	2500 – 5000	
Intensive	5000 – 8000	
Very intensive	8000 – 15000	
Severe	> 15000	

➢ **Rainfall erosivity (*R*) factor**

In this study, the annual rainfall erosivity used the method of Zhang et al. (2002), which has been widely used in the Loess Plateau and the rest of China (Cheng et al., 2009; Xiao et al., 2015; Jiang et al., 2016). This method obtains annual rainfall erosivity using aggradations of half-month rainfall erovisity, which is estimated based on daily rainfall erosivity as below:

$$R = a\sum_{j=1}^{m} D_j^b \tag{3}$$

where D_j is equal to the actual rainfall if the actual rainfall is larger than the threshold value of 12 mm. For daily rainfall equal to or larger than the threshold value of 12 mm, D_j is the actual rainfall, otherwise D_j equals 0 (Xie et al., 2000). Many studies have found that daily rainfall less than 10 mm did not have an important impact on runoff and erosion (Wischmeier and Smith 1978). Xie et al. (2000) found that 12 mm could be the standard for describing erosive rainfall on the Loess Plateau, and this criterion has been widely accepted (Zhang 2003; Cheng et al. 2009).

Parameters of *a* and *b* vary with changes in rainfall characteristics, and are estimated with the empirical equation (4) and (5) (Zhang et al., 2002):

$$a = 21.586 \times b^{-7.1891} \tag{4}$$

$$b = 0.8363 + \frac{18.177}{P_{day}} + \frac{24.455}{P_{year}} \tag{5}$$

Where P_{day} is the average daily rainfall that is more than 12 mm, and P_{year} is the annual average rainfall for days with rainfall of more than 12 mm.

- **Soil erodibility (*K*) factor**

The Erosion/Productivity Impact Calculator method was used to calculate *K* factor. This equation is conducted by Zhang et al. (2008) and Rao et al. (2014) for revision, which makes it applicable to use in the study site.

$$\begin{aligned} K = {} & 0.1317 * \{0.2 + 0.3\exp[-0.0256 m_{sand}(1 - m_{silt}/100)]\} \times [m_{silt}/(m_{clay} + m_{silt})]^{0.3} \\ & \times (1 - 0.25OC/[OC + \exp(3.72 - 2.95OC)]\} \times \{1 - 0.7(1 - m_{sand}/100)/ \\ & \{(1 - m_{sand}/100) + \exp[-5.51 + 22.9(1 - m_{sand}/100)]\}\} \end{aligned} \tag{6}$$

Where m_{sand}, m_{silt} and m_{clay} are the sand fraction (%), silt fraction (%), clay fraction (%), respectively. *OC* is the percentage of organic carbon (%).

- **Slope length-steepness (*SL*) factor**

SL factor reflects the effect of slope gradient (*S*) and slope length (*L*) on erosion. This study used the formula for *L* factor defined and developed by Liu et al. (1994), and this equation has been widely used to calculate *SL* factor in China (Fu et al., 2011, Jiang et al., 2016). The *L* and *S* factors are determined by Equation (7) to Equation (10), respectively:

$$L = (l/22.13)^m \tag{7}$$

$$m = \beta/(1+\beta) \tag{8}$$

$$\beta = (\sin\theta/0.089)/\left[3.0 \times (\sin\theta)^{0.8} + 0.56\right] \tag{9}$$

$$S = \begin{cases} 10.8\text{Sin}\,\theta + 0.03, & \theta < 5° \\ 16.8\text{Sin}\,\theta - 0.5 & 5° \le \theta < 10° \\ 21.91\text{Sin}\,\theta - 0.96 & \theta > 10° \end{cases} \tag{10}$$

- **Vegetation cover management (*C*) factor**

C factor is the cover-management factor, which reflects the effect of cropping and management practices on erosion rates. To calculate C factor values requires collecting of detailed data regarding the cultivation systems, specific farming style, and residuals management systems. However, in the research area there is no large scale data about the spatial distribution of cover-management. Thus, the reference *C* values were assigned to the main LULC types according to Cheng et al., 2009 (Table 3-3).

Table 3- 3 *C* values under different LULC types in northern Shaanxi, adapted from Cheng et al. (2009)

LULC type	*C* value	LULC type	*C* value	LULC type	*C* value
Woodland	0.080	Grassland	0.240	Cropland	0.230
Water bodies	0.000	Built-up land	0.353	Bare land	1.000

➢ **Erosion control practices (*P*) factor**

As to *P* factor, it reflects the impact of support measures (e.g. growing terrace and contour tillage) to affect erosion rate. However, it is difficult to reflect the results of soil and water conservation measures at large scale (Fu et al., 2005). Slope gradient is a key factor for the soil loss on the Loess Plateau. For this reason, the slope-based Wener method (Lufafa et al., 2003) was applied to calculate *P* factor in equation (11), where *S* is the percentile slope gradient:

$$P = 0.2 + 0.03 \times S \tag{11}$$

3.3.2 Water yield quantification

Water yield is defined as the average amount of fresh water that runs off in an unregulated watershed. The InVEST annual water yield model assumptions are based on processes that are analysed at the (sub) watershed scale. It estimates the total annual water yield (*Y*) for each pixel (*x*) of the watersheds as total annual rainfall (*P*) minus total annual actual evapotranspiration (*AET*) (Equation 12).

$$Y_x = (1 - \frac{AET_x}{P_x}) \cdot P_x \tag{12}$$

$\frac{AET_x}{P_x}$ is based on an expression of the Budyko curve proposed by Fu (1981) and Zhang et al. (2004) as follows:

$$\frac{AET_x}{P_x} = 1 + \frac{PET_x}{P_x} - \left[1 + \left(\frac{PET_x}{P_x}\right)^w\right]^{1/w} \tag{13}$$

where *w* is a non-physical parameter that characterizes the natural climatic-soil properties, and it can be expressed in equation (14).

PET is the potential evapotranspiration and *w* is a non-physical parameter that characterizes the natural climatic-soil properties.

$$w = Z * \frac{AWC_x}{P_x} + 1.25 \tag{14}$$

where *w* is related to the plant available water content (*AWC*), precipitation and the constant Z which captures the local precipitation pattern and additional hydrogeological characteristics (Zhang et al., 2004).

PET can be expressed in as follows (equation 15):

$$PET_x = K_c(l_x) * (ET_0)_x \tag{15}$$

Where ET_0 is the reference evapotranspiration and $K_c(l_x)$ is the vegetation evapotranspiration coefficient associated with the LULC type ℓ_x on pixel *x*.

Hargreaves and Samani (1985) introduced maximum, minimum temperature and extraterrestrial radiation to calculate solar radiation, and then they established the well-known HS model for ET_0 estimation. It is considered as one of the simplest and accurate ET_0 estimation methods (Jensen et al., 1997). HS model is a suitable method for calculating ET_0 in semi-arid and arid regions (Lopez-Urrea et al., 2006; Almorox et al., 2015). In the past decades, many papers have put much effort on the calibration of HS model in China (Luo et al., 2014; Feng et al., 2016). Moreover, Zhao et al. (2004) assessed 3 temperature-based methods for estimating ET_0, and their results indicated that HS model provided the most accurate ET_0 estimation in the Loess Plateau. Thus, in this study ET_0 was calculated via the HS model (Equation 16).

$$ET_o = 0.0023 * RA * (T_{avg} + 17.0) * (T_{\max} - T_{T\min})^{0.5} \tag{16}$$

where *RA* is extraterrestrial radiation (mm/month) at the top of the Earth's atmosphere on a horizontal surface. *RA* can be calculated according to the equation (17) (Allen et al., 1998). T_{avg} is average daily temperature (◦C) defined as the average of the mean daily maximum and mean daily minimum temperature, and T_{max} and T_{min} (◦C) is the mean daily maximum and mean daily minimum temperature, respectively.

$$RA = \frac{24*60}{\pi} G_{sc} d_r \left[\omega_s \sin(\delta)\sin(\varphi) + \cos(\delta)\cos(\varphi)\sin(\omega_s) \right] \quad (17)$$

where G_{sc} is solar constant = 0.0820 $MJ\ m^{-2}\ min^{-1}$, d_r is inverse relative distance Earth-Sun, ω_s is sunset hour angle, φ is latitude, and solar decimation is given by δ.

K_c values vary predominately with the specific vegetation characteristics. In this study, *Kc* values among different vegetation types were obtained from the previous studies (Table 3-4).

Table 3- 4 *Kc* value under different vegetation types in the northern Shaanxi

LULC type	**Vegetation type**	**Kc coefficient**	**Reference**
Woodland	*Hippophae rhamnoides*	0.98	Wu et al., 2008
Grassland	*Bothriochloa ischaemum*	0.85	
Cropland	Maize	1.20	Wang et al., 2015
	Winter wheat	1.17	
	Bean	1.10	Allen et al., 1998
	Paddy	1.20	
Water bodies		1.00	Sharp et al., 2016
Bare land		0.70	
Built-up land		0.42	

3.3.3 Water-related ES change rate analysis

Water-related ES change rate is used to detect the change of soil erosion and water yield before (1988-2000) and after implementation the ERPs (2000-2015). Since water yield quantification is based on the watershed scale, the water-related ES change rate analysis is also based on watershed scale. Water-related ES change rate maps were created. The change rate can be expressed as follow:

$$K_{wy} = \frac{wy_{final} - wy_{initial}}{wy_{initial}} * \frac{1}{T} * 100\% \quad (18)$$

Where K_{wy} is the change rate of water yield, $wy_{initial}$ is the value of water yield in the initial year, while wy_{final} is the value of water yield in the final year. T is the study period.

$$K_{se} = \frac{se_{final} - se_{initial}}{se_{initial}} * \frac{1}{T} * 100\% \quad (19)$$

Where K_{se} is the change rate of soil erosion, $se_{initial}$ is the value of soil erosion in the initial year, while se_{final} is the value of soil erosion in the final year. T is the study period.

3.4 Relationship analysis

3.4.1 Impacts of LULC change on water-related ES

3.4.1.1 Geographically weighted regression model

In geospatial analysis, the data are drawn from geographical units (e.g. pixel unit, watershed unit) and a single regression equation is estimated. One important assumption underlying this approach is that the relationships of interest are stationary or homogeneous spatially. This has the effect of producing global parameter estimates which are assumed to apply equally over the whole region. While the global perspective is effective in handling spatial dependence, it is not capable of exploring spatial non-stationarity or identifying site-specific associations (Brunsdon et al., 1996). To fill this gap, Fotheringham et al. (1997) developed the geographically weighted regression (GWR) model. The GWR model extends the traditional regression framework by allowing parameters to be estimated locally. The GWR model was employed to analyse the impacts of LULC changes on water-related ES in this study. It has been widely used to examine spatially varying relationships between LULC change and ES (e.g. Tu and Xia 2008; Javi and Mokhtari 2014).

The global regression model is expressed as:

$$y_i = \beta_0 + \sum_{i=1}^{p} \beta_i x_i + \varepsilon \tag{20}$$

where y_i represents dependent variable; x_i denotes independent variables; and β_0 and β_i denote intercept and coefficients, respectively. P denotes the number of independent variables, and ε represents error.

The GWR extends this global regression framework to estimate the spatial varying relationships by generating a set of local-specific coefficients. The equation can be expressed as follows:

$$y_i = \beta_0(u_j, v_j) + \sum_{i=1}^{p} \beta_i(u_j, v_j) x_{ij} + \varepsilon_j \tag{21}$$

Where $\beta_0\,(u_j, v_j)$ is the intercept value at location j; $(u_j,\ v_j)$ represents the coordinates at location j; $\beta_i\,(u_j, v_j)$ is the local regression coefficient for the x_i independent variable at location j; ε_j is the random error term at location j.

To calibrate the GWR model, it is assumed that the observed data close to location j

have a greater influence in the estimation of the $\beta_i(u_j,v_j)$ parameters than the data located farther from observation *j*. The estimation of $\beta_i(u_j,v_j)$ can be expressed as

$$\beta^{'}(u_j,v_j) = \left[X^T W(u_j v_j) X\right]^{-1} X^T W(u_j,v_j) Y \tag{22}$$

Where $\beta^{`}(u_j,v_j)$ represents the estimates of the location-specific parameters; X is a data matrix of the independent variables; Y is a data vector of the dependent variable. $W(u_i,v_i)$ is an n × n matrix whose diagonal elements denote the geographical weighting of observation data for location *j*.

The GWR is calibrated by weighting all observations around a sample point using a distance decay function, assuming the observations closer to the location of the sample point have the higher impact on the local parameter estimates for the location. Gaussian distance decay can be used to express the weight function:

$$w_{ij} = \exp\left(-\frac{d_{ij}^2}{h^2}\right) \tag{23}$$

where h is the bandwidth, which produces a decay of influence with distance. D_{ij} is the measure of distance between location i (x_i,y_i) and j (x_j,y_j), and the distance which is usually defined as a Euclidean distance can be expressed as below:

$$d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i + y_j)^2} \tag{24}$$

The optimal bandwidth was determined by minimizing the corrected Akaike Information Criterion (*AICc*) in this study. The *AICc* value for the GWR model is expressed as (Hurvich and Simonoff 1998):

$$\text{AICc} = 2\text{nln}(\delta) + \text{n}\frac{n+tr(s)}{n-2-tr(s)} \tag{25}$$

where δ is the standard deviation for random error. $Tr(s)$ is the function of bandwidth.

3.4.1.2 Geographically weighted regression model assessment

As with any GWR study, it is important to estimate the parameters of the global regression, such as ordinary least squares (OLS), so that this benchmark model can be compared to its GWR counterpart (Fotheringham and Charlton 1998). Two statistical parameters were employed to compare the model performance between GWR and OLS models: *AICc* and adjusted R^2. *AICc* is a method of selecting bandwidth in the GWR model, while it is also used to assess the GWR model. The model with a lower *AICc* and higher adjust R^2 indicates better performances (Brown et al., 2002).

Spatial autocorrelation in model residuals of OLS and GWR are examined by Moran's Index (*I*) (Equation 26-28), so as to compare their ability to address the spatial autocorrelation issues.

$$I = \frac{n}{S_0} \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} W_{i,j} (x_i - x)(x_j - x)}{\sum_{i=1}^{n} (x - \bar{x})^2} \quad (26)$$

$$S_0 = \sum_{i=1}^{n} \sum_{j=1}^{n} W_{i,j} \quad (27)$$

$$W_{i,j} = 1 / d_{i,j} \quad (28)$$

where *n* is the number of sub-regions; x_i is the variable of interest in sub-region *i*; x_j is the variable of interest in sub-area *j; x* is the mean, and W_{ij} represents the weighting between sub-regions of *i* and *j.*

In order to avoid the potential multicollinearity among all variables, firstly, the dependent variables in this study are the change rates of soil erosion and water yield in the pre-ERPs and ERPs periods. Accordingly, the independent variables include the change rates of cropland, woodland, and grassland in both time periods. The value of soil erosion and water yield are calculated from several related factors (e.g. LULC factor). In the USLE model, vegetation cover management I factor is one of factors that used to calculate soil erosion. The reference *C* values were assigned to the main LULC types. In the InVEST water yield model, vegetation evapotranspiration coefficient (*Kc*) is one of factors that used to calculate water yield, and *Kc* values associated with the LULC types. Secondly, only one independent variable was used for GWR model. And then all independent variables were combined for models to compare the overall performance of goodness-of-fit with that of single independent variable model. Condition numbers are used to evaluate local collinearity. Condition numbers indicate how sensitive a linear equation solution is to small changes in matrix coefficients. Results are unstable in the presence of local collinearity as indicated by a condition number greater than 30.

3.4.1.3 Impacts of LULC change on water-related ES

In this study, the local coefficients and the local R^2 values produced by the GWR models are mapped to give a clear visualization of the spatial variations in the relationships between LULC and water-related ES. The local coefficients for an independent variable states how the change in a dependent variable is affected by a unit change in the independent variable at the regression model, which can be used to reflect the relationships between the independent variable and dependent variable in different sub-watersheds. In particular, the dependent variables are the change rates of soil erosion and water yield in the pre-ERPs and ERPs periods, while independent variables include the change rates of cropland, woodland, and grassland in both time periods. For example, if positive coefficient exists between the change rate of cropland and the change rate of soil erosion, it indicates that higher cropland change rate is linked to higher soil erosion change rate. The single change rate of LULC and water-related ES is used to describe the change speed of regional LULC and water-related ES, respectively. Local R^2, ranging from 0 to 1, shows how this model can fit the data in regression models. The local R^2 values from the GWR model reflect the abilities of the each LULC variable to explain the spatial variance in water-related ES at different sub-watersheds, respectively.

3.4.2 Relationships between soil erosion and water yield

3.4.2.1 Analysis framework

Generally, ES trade-offs occur when human interventions enhance the output of an ecosystem service while negatively affect the provision of other services (De Groot et al., 2010). A synergy is a situation where the use of one ES directly increases the benefits supplied by another service (Howe et al., 2014). In northern Shaanxi, soil erosion is the main environmental constraint on environmental quality and socioeconomic development (He et al., 2004; Fu et al., 2011). Thus, we defined that annual soil erosion decrease is an improvement. However, northern Shaanxi is also located in the arid and semi-arid regions. Water is one of the most important factors for large-scale afforestation and social economic development in this region. We defined annual average water yield decline as water provision service decrease in northern Shaanxi.

Therefore, we developed the following interactions between ES based on the respective LULC states in the study site.

- Synergy: a win-win situation that involves a mutual improvement of both soil erosion and water yield.

- Trade-off: A win-lose or lose-win situation that involves losing one service (e.g. water yield) in exchange for gaining another (e.g. soil erosion).
- No change: No changes in any of the considered water-related ES.

3.4.2.2 Relationship analysis

Under this framework, we analysed synergies or trade-offs between soil erosion and water yield before and after implementation of the ERPs. The methodology used in this section includes the Pearson's correlation model. All Pearson's correlation analysis is based on the watershed scale because quantifying the value of water yield is based on the watershed scale.

3.5 Scenario analysis

Scenario analysis included LULC change scenarios and statistical downscaling of the RCPs 4.5 scenario. The changes in water-related ES need to consider future climate change. In arid and semi-arid regions where precipitation is an important environmental factor, the variation of precipitation can have a significant impact on the local ecological systems (Lioubimtseva et al., 2005). The change of precipitation is expected to alter surface evaporation, transpiration, and soil water content, which in turn can affect water yield changes in a watershed and hydrologic budgets across broad spatial scales (Wullschleger and Hanson, 2006). Figure 3-8 shows the overview of scenario analysis framework.

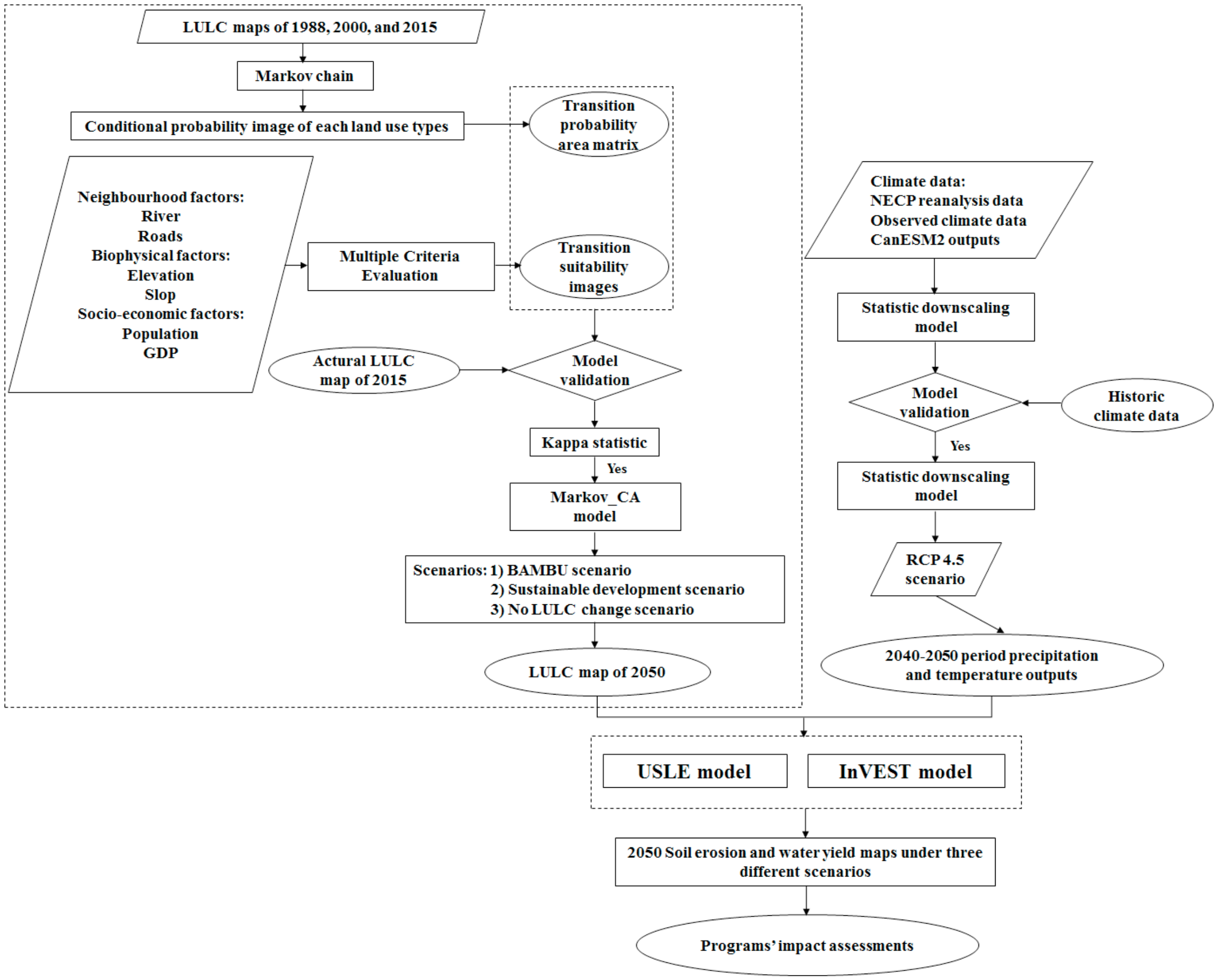


Figure 3- 8 Overview of scenario analysis in this study

3.5.1 LULC change scenario design

Three LULC scenarios were designed: protection, business-as-usual (BAU) and No LULC change scenarios in this study. The extreme scenarios, such as rapidly increase croplands or decrease woodlands, are not considered, and the time period of land planning scenario take around 35 years (to 2050) in this study. Firstly, geological and geomorphologic characteristics and long-term farming practices, combined with huge population pressures, have led to severe environmental degradation in this region. The purpose of ERPs is to repair damaged ecosystem functions. The situation of large-scale croplands increase might not appear in northern Shaanxi. Secondly, many papers (e.g. Wang et al., 2007; Cao 2008; Feng et al., 2012) argued that massive afforestation without considering the growth conditions might not achieve the expected ecological goals, and even causing potential environmental problems. The middle-term land use planning, by contrast, is more applicable for various natural conditions and needs much lower operational costs. Inevitably, contradiction always exists between ecological targets and economic benefits.

In the BAU and protection scenarios, woodlands and grasslands were designed to increase but the difference was that the degree of increase was different in two scenarios.

- BAU scenario

In this scenario, we assumed a situation where ERPs are not implemented, which means woodlands and grasslands are expected to slightly increase. In other words, the LULC change patterns are similar the LULC change patterns from 1988 to 2000.

- Protection scenario

In this scenario, we assumed a situation where the ERPs will still be implemented, and where the LULC change patterns are similar to the LULC change patterns between 2000 and 2015. It means the woodlands and grasslands are expected to increase and croplands are expected to decrease in northern Shaanxi. The woodlands and grasslands are mainly converted from croplands and bare lands in the study site.

- No LULC change scenario

This scenario is to characterize the interactive roles of climate in the changes of water-related ES, especially for water yield changes. In this scenario, we focused on detecting impacts of precipitation and temperature changes on water-related ES. In other words, current LULC map in 2015 will be used in this scenario.

3.5.2 LULC change scenario modeling

Although we designed three LULC change scenarios, No LULC change scenario is actually using the LULC map in 2015. Thus, LULC change scenario modelling focused on the BAU and protection scenario. The Markov- Cellular Automata (CA) model, which incorporates the theories of Markov and CA, is about the time series and space for LULC forecasting. The model's input includes a base-year LULC map, the transition matrix produced by the Markov chain, and a collection of suitability map for each land use type. The multiple criteria evaluation (MCE) is widely used to score the suitability of each affecting factor and produce the input as transition rule for the CA model (Eastman 2006).

3.5.2.1 Markov chain for LULC temporal change

In Markov chain model, LULC changes are thought of as a stochastic process in which the probability distribution of the current state is conditionally independent of the path of past states. It is a model of the system where the next state is solely depending on the current state (Myint and Wang 2006). The state at a particular time *t* is dependent exclusively on the state at previous time step *t-1*. The transition probability equation can be written as:

$$S(t) = P_{ij} \times S(t-1) \tag{29}$$

where $S(t)$ and $S(t-1)$ are the system status at the time of t and $t-1$. P_{ij} is the transition probability matrix in a state.

3.5.2.2 Suitability maps for LULC change

MCE is a multi-attributes decision-making method for land suitability analysis in land use planning, environmental hazards and sustainable development (Agarski et al., 2012). MCE combines map overlay and user preferences that can be divided into two main parts – factor selection and suitability score assignment. Factors used in MCE usually include socio-economic and environmental dimensions, and translate their information into measurable parameters. In this study, typical socio-economic and environmental factors, including population, and the GDP, slope, elevation, distance to roads and distance to river, and protection area were selected to calculate transition potential maps of LULC. The details of factor selection are as follows :

- Slope: According to the GGP, the croplands more than 25 degrees were directly converted to woodlands and grasslands. Thus, the slope which is more than 25 degrees in the study site will be used as one of the constraint factors in the BAU scenario. It means the croplands more than 25 degrees will not be converted to woodlands and grasslands under this scenario. Moreover, slop will be used as one of the constraint factors in the protection scenario. The croplands more than 25 degrees will be converted to woodlands and grasslands. The Boolean method is used to create slope constraint map.
- Population and the GDP: Although economic development in northern Shaanxi has lagged far behind progress on the national average, the GDP in this region in recent years increased fast (Figure 3-11a). Moreover, the population in northern Shaanxi

showed an increase tendency from 1988 to 2013. Based on previous studies, the accelerated industrialization and urbanization following population growth in China have greatly affected LULC change through increasing built-up areas and urban sprawl (Wu et al., 2004). With the continuous growth of China's economy, massive croplands converting to non-agricultural lands may occur without appropriate planning and management of existing land resources (Long et al., 2007). Thus, the GDP and population were considered as the social-economic driving factors in this study, and they will be used for both scenarios.

- Elevation: LULC changes caused by human activities are limited by the elevation factor in the Loess Plateau (Fu et al., 2006). For example, croplands abandonment often occurred in the highest or lowest regions as elevation differences between ridges and valley bottoms can influence climate variations (Shrestha and Zinck 2001). Moreover, built-up lands are often located in the flat regions with good traffic condition and water supply. We considered the elevation factor as a driving force factor in both scenarios.
- Distance to roads and river: Due to natural (e.g. topographic) constraints, land use activities have focused on riverside areas, and these regions usually have more opportunities to develop agricultural and industrial facilities compared with mountain areas. Moreover, many studies have shown that transportation networks affect LULC change (Frazier and Kockelman 2005). In this study, distance to roads and distance to river factors will be used in both scenarios and they were created as raster maps by using Euclidean distance method.
- Protection areas: In all scenarios, woodlands and grasslands will be protected, which means they will not be allowed to convert to another LULC type. The Boolean method is used to create protection area maps.

3.5.2.3 Model implementation

Model implementation consisted of two steps, namely model validation and model prediction. For model validation, only the BAU scenario is validated due to data limitation. In particular, the Markov_CV model firstly was used to simulate LULC change in 2015. LULC maps for the years 1988 and 2000 were entered into a Markov chain to calculate the land transition possibility matrix for the year 2015. Secondly, the suitability maps for each LULC were produced using the MCE method. Then, these LULC demands were translated into spatial allocation using the CA model to simulate 2015 LULC changes. The main steps include determining CA filters and selecting iteration number. CA filters can produce a clear sense of the space weighting factor, which can be changed according to the current adjacent cellular state.

In this study, the validation results were assessed to measure the goodness of fit between the observed and the simulated LULC maps. It means that simulated LULC map for 2015 was compared with the satellite-derived map for 2015 which is provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (DCRES, CAS). Using an error matrix to represent accuracy has been recommended by many researchers (Rwanga and Ndambuki 2017). It is computed by dividing the total correct by the total number of pixels in the error matrix. The equation can be expressed as:

$$K_{overall} = \frac{N_{correct}}{N_{total}} \times 100 \tag{30}$$

Where $K_{overall}$ is the overall accuracy; $N_{correct}$ is the number of the correct pixel; and N_{total} is the total number of pixel.

3.5.3 Statistical downscaling of the RCPs 4.5 scenario

3.5.3.1 Downscaling scenario selection

The Intergovernmental Panel on Climate Change (IPCC) has published a source of influential reports on the state of climate change since 1990 (http://www.ipcc.ch/). In 2014, the IPCC fifth assessment (AR5) report assessed 21st century projections from a new range of socio-economic scenarios for climate modelling—the RCPs (Table 3-5). RCPs are time and space dependent trajectories of concentrations of greenhouse gases and pollutants resulting from human activities, including changes in land use. RCPs provide a quantitative description of concentrations of the climate change pollutants in the atmosphere over time as well as their radiative forcing in 2100. Moreover, the new insights into implementation of air pollution control measures were developed more recently (Smith and Wigley 2006).

Table 3- 5 Main emission characteristics of each RCPs, adapted from van Vuuren et al. (2011)

Scenarios	Major characteristics

RCP 2.6 Low missions	Developed by the PBL Netherlands Environmental Assessment Agency; it is a scenario that stabilizes radiative forcing level reaches 3.1 W/m^2 by mid-century but returns to 2.6 W/m^2 by 2100.
RCP 4.5 Intermediate emissions	Developed by the Pacific Northwest National Laboratory's Joint Global Change Research Institute (JGCRI), United States; it is a scenario that stabilizes radiative forcing level at 4.5 Wm^{-2} in the year 2100 without ever exceeding that value. Emissions in RCP 4.5 peak around 2040, then decline.
RCP 6.0 Intermediate emissions	Developed by the National Institute for Environmental Studies (NIES), Japan; radiative forcing level is designed at 6.0 Wm^{-2} by 2100, and emissions peak around 2080, then decline.
RCP 8.5 High emissions	Developed by the International Institute for Applied Systems Analysis (IIASA), Austria; in this scenario, the greenhouse gas emissions and concentrations increase considerably over time, leading to a radiative forcing of 8.5 W/m^2 in the year 2100.

RCPs scenarios considered the different degree of emissions, such as low (RCPs 2.6), intermediate (RCPs 4.5 and 6.0), and high (RCPs 8.5) emission scenarios. The RCPs 4.5 scenario was selected because many studies have integrated RCPs 4.5 scenario into LULC changes scenarios to evaluate their effects on ES (e.g. Kim et al., 2013; Wu et al., 2013; Couture et al., 2017). Moreover, in order to downscale RCPs scenarios, the use of 'predictors' is needed. The 'predictor variables' provide daily information concerning the large-scale state of the atmosphere, while the 'predictand' describes conditions at the site scale (i.e. temperature or precipitation observed at a station). Large-scale predictor variable information in this study is provided by the Canadian Centre for Climate Modelling and Analysis of Environment and Climate Change Canada (http://ccds-dscc.ec.gc.ca/index.php?page=dst-sdi). Only predictor variables of RCPs 2.6, 4.5, and 8.5

scenarios are provided by their data package. Thus, RCPs 4.5 scenario, was chosen to downscale the precipitation and temperature in the period 2040s-2050s in northern Shaanxi.

3.5.3.2 Statistical Downscaling Model

The usual tools used to project climate change are General Circulation Model (GCM), which are computer models that mathematically represent various physical processes of the global climate system. However, due to their huge computational load, GCM usually used coarse grids (e.g. 100 – 500km grid cell) that prevent adequate spatial resolution of regional processes. Therefore, GCM outputs are usually considered at global or continental scales. Thus, the purpose of downscaling is to increase the spatial or temporal resolution of GCM outputs. Generally, downscaling methods include dynamic downscaling and statistical downscaling. Table 3-6 makes a comparison between dynamical and statistical downscaling approaches. Dynamical downscaling refers to the use of a regional climate model (RCM) driven by a GCM to simulate regional climate. An RCM is similar to a GCM but has higher resolution and additional regional information, which can represent better local atmospheric processes, while statistical downscaling involves the establishment of empirical relationships between historical large-scale atmospheric and local climate characteristics. Once a relationship has been validated, future large-scale atmospheric conditions projected by GCMs are used to predict future local climate characteristics. In this study, statistical downscaling was employed to downscale the GCM output, because statistical methods can provide station-scale climate information. Moreover, considering the financial and technical support, using statistical downscaling method was more realistic in this study.

Table 3- 6 Comparison of dynamic and statistical downscaling, adapted from Wilby et al. (2002)

	Dynamic downscaling	**Statistical downscaling**
Advantages	➢ Based on physical processes, more details about atmospheric and surface processes occurring at sub-GCM grid scale;	➢ Computationally inexpensive and efficient; ➢ Can provide any scale, down to station-level information;

	➢ Not constrained by historical record so that novel scenarios can be simulated.	➢ Methods, ranging from simple to elaborate, are flexible enough to tailor for specific purposes
Disadvantages	➢ Intensive computationally and require complex modeling of physical processes and high level of expertise to interpret results; ➢ The quality of downscaling results depends on the driving GCM information;	➢ Need high quality observed data which may be unavailable for many regions; ➢ Assumes that relationships between large and local-scale processes will not change in the future

Downscaling of the RCPs 4.5 scenario to the local level is done by the Statistical DownScaling Model (SDSM). The SDSM, developed by Wilby et al. (2002), incorporates the weather generator and multiple linear regression based on a large number of atmospheric predictors. The primary principle of SDSM is to establish the statistical relationship between the predictands (e.g. local precipitation) and predictors (e.g. large-scale climate variable) and then determine the required predictors for the weather generator at each individual grid point (Wilby et al., 2002).

Unlike the simple multiple linear regression, the temperature and precipitation variables are modeled as an unconditional and conditional process in the statistical downscaling model (SDSM), respectively. In the conditional method, daily precipitation depends on an intermediate variable such as wet-day occurrence (w_i). Wet-day occurrence on day i is linearly dependent on predictor x_{ij}:

$$W_i = \alpha_0 + \sum_{j=1}^{n} \alpha_j X_{ij} \tag{31}$$

where α_j is the estimated regression coefficient. The value of w_i varies according to prevailing large-scale weather conditions between 0 and 1. Here we define a wet-day as any day with non-zero precipitation total. Precipitation occurs if $r \leq w_i$, where r_i is a computer-generated uniformly distributed stochastic number. Then, the total precipitation (P_i) downscaled on day *i* given that precipitation occurs is modeled by

$$P_i = \beta_0 + \sum_{j=1}^{n} \beta_j x_{ij} + \delta_i \tag{32}$$

where β_j is the estimated regression coefficients, ε is a normally distributed stochastic error term.

The SDSM modelling involves five major steps to downscale temperature and precipitation (Table 3-7).

Table 3- 7 Summary of the SDSM, adapted from Wilby et al. (2002)

Major steps	Description
Screening variable	This step is to identify appropriate downscaling predictor variables, in order to establish empirical relationships between the predictands (e.g. local precipitation) and predictors (e.g. mean sea level pressure).
Model calibration	This step is to establish monthly regression model using selected predictors. A simulation is performed using the calibration period (1981-1990) of each temperature and precipitation data series.
Model validation	This step is to validate simulation daily temperature and precipitation data series for the period of 1991-2001 using the calibrated regression model.
Scenario generating	This step is to produce future temperature and precipitation supplied by CanESM2.
Hydrologic application	Downscaled temperature and precipitation data series serve as inputs to drive USLE and InVEST models.

3.5.4 Scenario analysis

Three LULC change scenario outputs (i.e. BAU, protection, and No LULC change), and downscaled average annual precipitation and *ET0* in the period 2040-2050s are used to drive the USLE and InVEST models to estimate the value of soil erosion and water yield in 2050, and to further analyse the potential impacts of the ERPs on water-related ES under these different scenarios. The potential impact analysis focuses on the temporal and spatial aspects. As for spatial analysis, soil erosion and water yield spatial distribution maps in 2050 under different LULC change scenarios and in 2015 are presented. Soil erosion is classified into 6 class based on the Ministry of Water Resource of the People's Republic of China (1997), and all soil erosion maps in 2050 are compared with the map in 2015 at pixel-based scale. All water yield maps in 2050 are compared with the map 2015 at the sub-watershed scale. As for temporal analysis, the value of soil erosion and water yield under different scenarios are compared with the value of these two ES in 2015 at regional scale. Basically, as for soil erosion, if the values of scenario output are lower than the value in 2015, we consider that the LULC change scenarios can have a positive influence on soil erosion control. As for water yield, the values of scenario output are higher than the value in 2015, we consider that the LULC change scenarios can help increase the amount of water yield in the study site. Finally, the different scenario maps are also compared with each other at sub-watershed scale, while the value of soil erosion and water yield under different scenarios are compared with each other. This is to examine which scenarios can reduce negative trade-offs between soil erosion and water yield.

3.6 Data sources

In our study, we mainly used biophysical data (i.e. land use, climate, soil, elevation), and the datasets were obtained from online data sharing platforms and scientific organizations.

3.6.1 LULC datasets

LULC maps for 1988, 2000, 2008, and 2015, provided by the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (DCRES, CAS), were derived from Landsat Thematic Mapper I / Enhanced Thematic Mapper (ETM) images (Figure 3-9). Digital maps were retrieved with a resolution of 30 m. The original LULC maps have a total of 25 different classes for 1988, 2000, and 2008 and 23 different classes for 2015 (Table 3-8). The original classification is too numerous and specific for this analysis, therefore the categories were grouped into 6 aggregated classes of LULC: Cropland, Woodland, Grassland, Water bodies, Bare land and Built-up land.

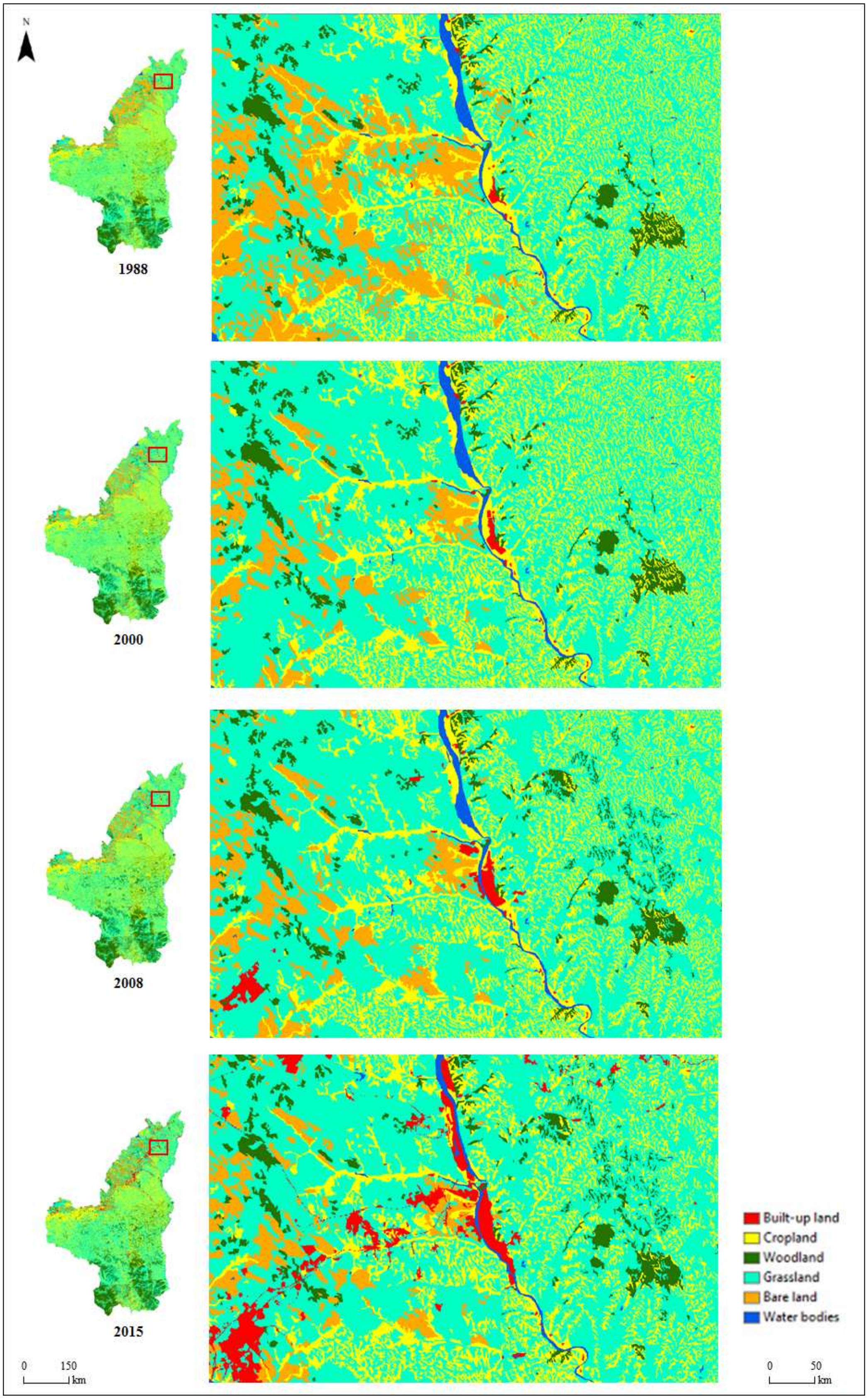


Figure 3- 9 Time series maps of LULC in northern Shaanxi from 1988 to 2015

Table 3- 8 Description of LULC types in this study

LULC types used in this study	Original LULC types in Liu et al. (2005)	Description
Cropland	Dry land	Cropland for cultivation without irrigating facilities.
	Paddy land	Cropland that has enough water supply and irrigation facilities for planting paddy rice, lotus etc.
Grassland	Dense grassland	Grassland with canopy coverage greater than 50%.
	Moderate grassland	Grassland with canopy coverage between 20% and 50%.
	Sparse grassland	Grassland with canopy cover between 5% and 20%.
Water bodies	Stream and rivers	Lands covered by rivers and stream.
	Lakes	Lands covered by lakes.
	Reservoir	Man-made facilities for water reservation.
	Permanent ice and snow	Lands covered by perennial snowfields and glaciers.
	Beach and shore	Lands between high tide level and low tide level.
	Bottomland	Lands between normal water level and flood level.
Built-up land	Urban built-up	Lands used for urban.
	Rural settlements	Lands used for settlements in villages.
	Others	Lands used for factories, quarries, mining, oil-field slattern outside cities and lands for

		special uses such as transportation and airport.
Bare land	Bare soil	Bare exposed soil with less than 5% vegetation cover.
	Bare rock	Bare exposed rock with less than 5% vegetation cover.
	Sandy land	Sandy land covered with less than 5% vegetation cover.
	Gobi	Gravel covered land with less than 5% vegetation cover.
	Salina	Lands with salina accumulation and sparse vegetation.
	Swampland	Lands with a permanent mixture of water and herbaceous or woody vegetation that cover extensive areas.
	Others	Other lands such as alpine desert and tundra.
Woodland	Forest	Natural or planted forests with canopy cover > 30%.
	Shrub	Lands covered by trees less than 2 m high, the canopy cover > 40%.
	Woods	Lands covered by trees with canopy cover ranges from 10% to 30%.
	Others	Other lands such as alpine desert and tundra.

In order to understand LULC changes in China, eight institutions under the Chinese Academy of Sciences have built a national LULC change temporal and spatial database since the 1990s. This project, namely the National Resources and Environmental Database, is essentially the fundamental work to study LULC dynamics, and to further analyse the driving forces behind them and to predict future LULC changes in China. This database has been widely used to detect LULC changes in China (Liu et al., 2002). The main data sources are Landsat TM digital images. Apart from that, the China-Brazil Earth Resources Satellite one data were also used to acquire LULC information. For the LULC map validation, the CAS usually conducted a field survey to evaluate the classification accuracy (Liu et al., 2003.). In particular, LULC map in 2000 showed that the overall accuracy of the land cover classification for the 25 sub-classes is 92.9% (Liu et al., 2005). However, we did not find the specific overall accuracy for the other three years of LULC maps.

3.6.2 Water-related ES datasets

According to the USLE model, five parameters are needed for soil erosion calculation. Table 3-9 shows the details of these parameters. The resources for identifying their values are precipitation, LULC maps (Figure 3-9), terrain data (Figure 3-10), and soil properties (Figure 3-11). In particular, daily precipitation data which the value is larger than the threshold value of 12 mm were selected to calculate rainfall erosivity according to equation 3 to 5.

Table 3- 9 Data sources for quantifying soil erosion

Data items	Brief description	Data sources
Precipitation	1988, 2000, 2008, and 2015 daily precipitation	The China Meteorological Data Sharing Service System
Soil types	Percentage silt, sandy, and clay, and organic matter in the topsoil.	The Harmonized World Soil Database
Soil organic matter	Percentage of organic matter in the topsoil.	
Elevation and slope	These data were obtained from a DEM with a 30m grid interval.	The Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model.
LULC maps	1988, 2000, 2008, and 2015 LULC maps with 30m spatial resolution.	The Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences

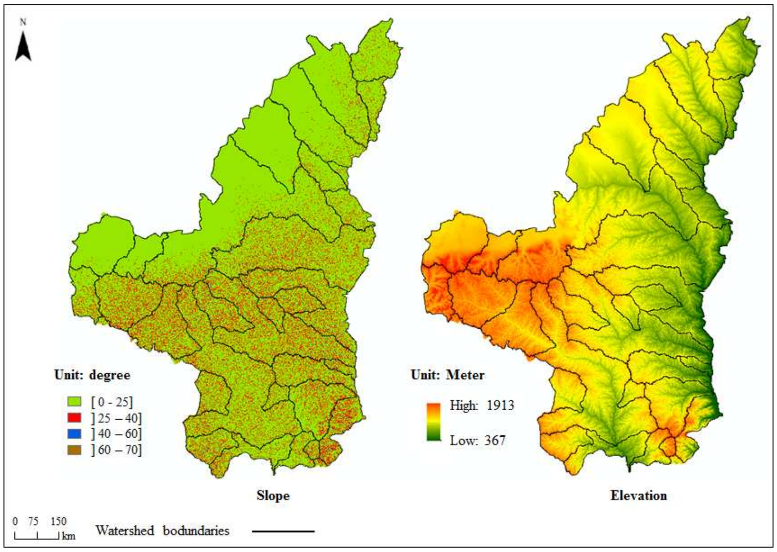


Figure 3- 10 Spatial distribution of slope and elevation in northern Shaanxi.

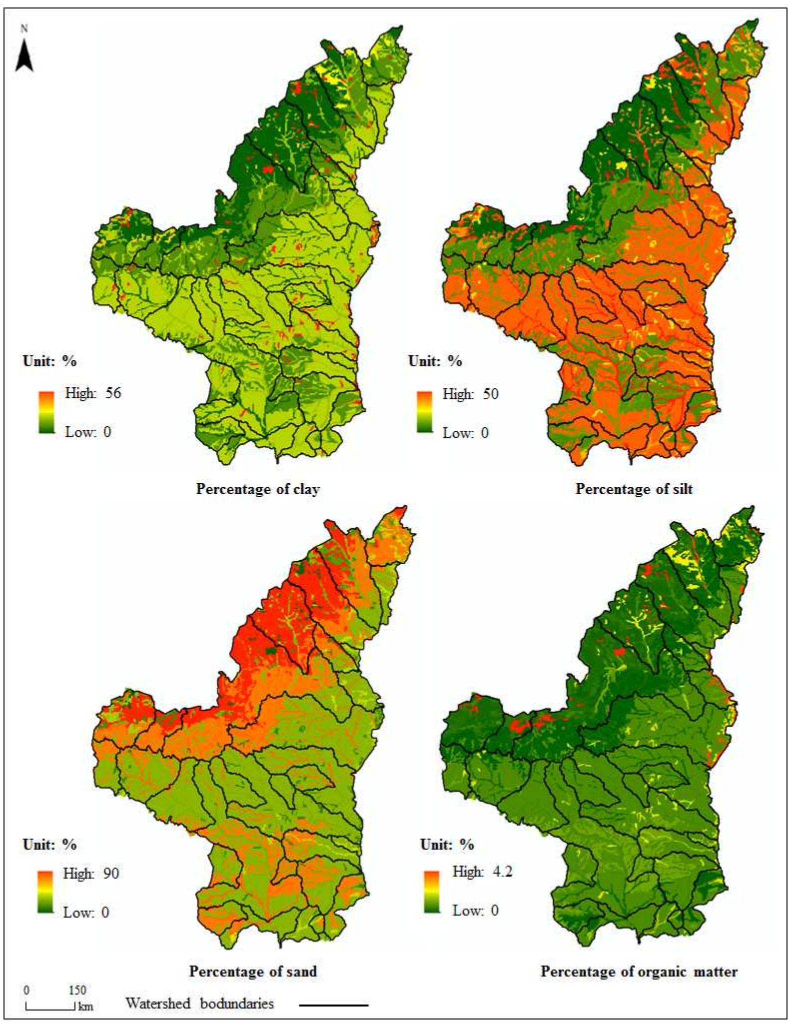


Figure 3- 11 Spatial distribution of soil texture and organic matter in northern Shaanxi.

The InVEST water model required six parameters. These were average annual precipitation (mm) which is calculated from daily precipitation, average annual *ET0* which is calculated from temperature, root restricting layer depth (mm), plant AWC, LULC maps, and sub-watersheds boundaries (Table 3-10).

Table 3- 10 Data sources for quantifying water yield

Data	Brief description	Data sources
Daily precipitation	Daily precipitation from 1988 to 2013	The China Meteorological Data Sharing Service System
Daily temperature	Daily temperature from 1988 to 2013.	
Plant AWC	Fraction of water that can be stored in the soil profile that is available for plants' use.	The Harmonized World Soil Database
Root restricting layer depth	Soil depth at which root penetration is inhibited.	
LULC maps	1988, 2000, 2008, and 2015 LULC maps with 30m spatial resolution.	The Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences
Sub-watershed boundaries	This data was obtained from the DEM with a 30m grid interval.	The Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model

3.6.3 LULC change scenarios and statistical downscaling datasets

To model LULC changes under different scenarios, the datasets included the rivers and roads vector data, population and GDP statistical data, DEM and LULC raster data (Table 3-11).

Table 3- 11 Data sources for modeling LULC change scenarios

Data type	**Description**	**Data source**
Rivers and roads	Shapefile format	The DIVA-GIS
Population	From 1988 to 2013, population in northern Shaanxi.	Shaanxi Statistical Yearbook (1987-2014)
GDP	We used the spatial GDP maps in 2005 and 2010 due to data limitation.	The Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences
LULC maps	1988, 2000, and 2015 LULC maps	
Slope and Elevation	These data were obtained from the DEM with a 30M grid interval.	The Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model

To develop statistical downscaling, the use of daily predictors is needed. The predictor variables provide daily information concerning the large-scale state of the atmosphere, while the predictand describes conditions at the site scale (i.e. temperature or precipitation observed at a station). Large-scale predictor datasets have been derived from the National Centre for Environmental Prediction (NCEP) reanalysis dataset for the calibration and the validation procedure of the SDSM, while GCM data for the climate scenario periods are from the second generation Canadian Earth System Model (CanESM2) outputs (Table 3-12). Figure 3-12 shows the geographical location of weather station used in this study.

Table 3- 12 Data sources for downscaling temperature and precipitation

Data	**Brief description**	**Data source**
	Precipitation and temperature are obtained from 10 weather station. For each station, 20	

Observed data	years (1981-2001) daily precipitation, maximum and minimum temperature records are used as predictand variables. The first 10 years (1981-1990) are used for calibration and the remaining 10 years (1991-2001) are used for validation purposes.	The China Meteorological Data Sharing Service System
The NCEP reanalysis data	It contains 26 daily predictors, which describe atmospheric circulation, thickness and moisture content at the surface, geopotential heights at 850 and 500 hPa.	The Canadian Climate Data and Scenarios website (http://ccds-dscc.ec.gc.ca/index.php?page=dst-sdi)
The CanESM2 outputs	The CanESM2 provides three scenarios-RCPs 2.6, 4.5, and 8.5 (representing a very low forcing scenario, medium stabilization scenario, and very high emission scenario, respectively) which are utilized to project future climate scenarios.	

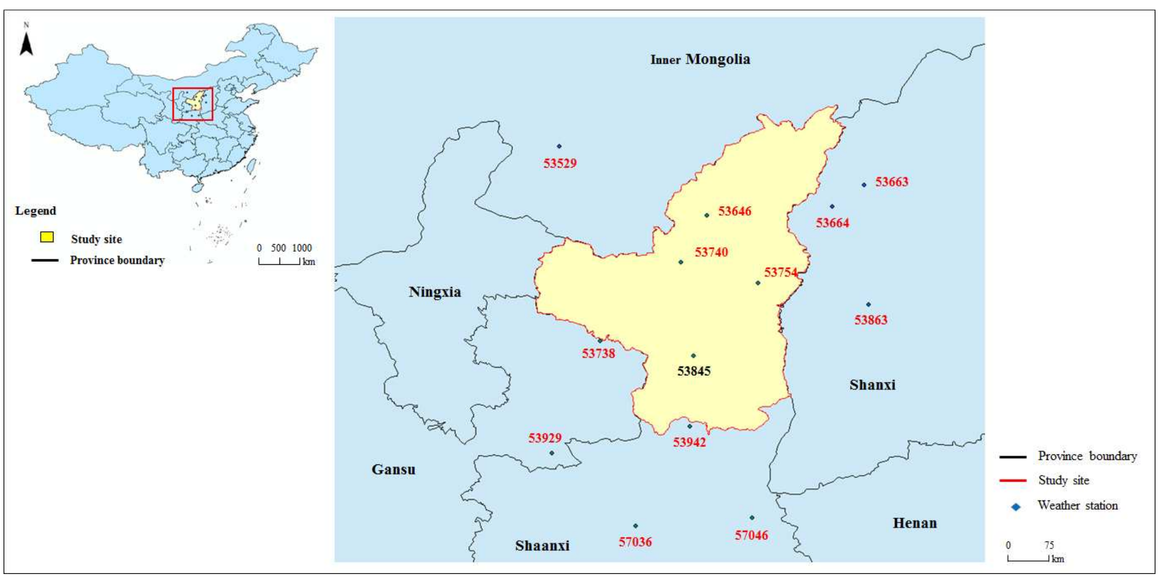


Figure 3- 12 Geographical location of weather stations used in this study

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Chapter 4 Land use and land cover change analysis

Summary

In Chapter 4, details regarding the spatial-temporal changes of LULC in northern Shaanxi before and during ERPs are presented. The major characteristic of LULC change during the ERPs period was a grassland and woodland increase as well as a cropland decrease in northern Shaanxi. In particular:

1. Vegetation areas (woodlands and grasslands) increased after implementation of the ERPs. Grasslands rapidly increased compared with woodlands during the ERPs period.
2. Cropland areas rapidly decreased after implementation of the ERPs in northern Shaanxi. In particular, croplands were more likely converted to grasslands. The cropland and grassland losses and gains occurred in the whole study site during ERPs period.
3. However, it was found that the annual change rates of woodland and grassland in each sub-watershed were not always positive during the ERPs period, indicating that woodlands and grasslands local decreases in some sub-watersheds during the ERPs period.

Résumé

Dans le chapitre 4, les détails concernant les changements spatio-temporels de l'occupation du sol dans le nord du Shaanxi, avant et pendant les PRE sont présentés. La principale caractéristique des changements d'occupation du sol au cours de la période des PRE est une augmentation des prairies et des terres boisées ainsi qu'une diminution des terres cultivées dans le nord du Shaanxi. En particulier :

1) Les zones de végétation (forêts et prairies) ont augmenté après la mise en place des PRE. Les prairies ont augmenté rapidement par rapport aux terres boisées pendant cette période.
2) Les superficies cultivées ont rapidement diminué après la mise en place des PRE dans le nord du Shaanxi. En particulier, les terres cultivées étaient plus susceptibles d'être converties en prairies. Les pertes et les gains des terres cultivées et des

prairies se sont produits sur l'ensemble du site d'étude au cours de la période des PRE.

3) Cependant, il a été constaté que les taux de changement annuels des terres boisées et des prairies dans chaque sous-bassin versant n'étaient pas toujours positifs pendant la période des PRE, indiquant des diminutions locales dans certains sous-bassins versants.

4.1 LULC temporal change analysis

Over the entire study period, there was an increase in the amount of land under Woodland, Grassland, Built-up land classes as well as a decrease in Bare land class. Croplands slightly increased from 1988 to 2000, while it rapidly decreased from 2000 to 2015. As shown in Table 4-1, grasslands were the dominant LULC types in the study site, taking up 42.56% of the total area in 1988 and 45.28% of the total area in 2015, followed by the croplands, accounted for 35.33% in 1988 and 31.42% in 2015. The total area of vegetation cover, including woodlands and grasslands, increased by 3696 km^2 from 1988 to 2015. The croplands showed a slight increase during the pre-ERPs period (1988-2000), while it decreased by 3305 km^2 during the ERPs period (2000-2015). Bare lands at the study site decreased from 5880 km^2 in 1988 to 4472 km^2 in 2015. In contrast, the built-up lands showed a stepwise increase from 262 km^2 in 1988 to 366 km^2 in 2008. However, it showed a rapid expansion after 2008, and reached 1227 km^2 in 2015.

Table 4- 1Area of LULC types in northern Shaanxi in different years

LULC types	**1988**		**2000**		**2008**		**2015**	
	km^2	**%**	**km^2**	**%**	**km^2**	**%**	**km^2**	**%**
Cropland	28134	35.33	28400	35.67	27029	33.95	25095	31.42
Woodland	10810	13.58	10984	13.8	12178	15.29	12229	15.31
Grassland	33890	42.56	34673	43.55	34897	43.83	36167	45.28
Water bodies	649	0.81	635	0.8	632	0.79	681	0.85
Built-up land	262	0.33	298	0.37	366	0.46	1227	1.54
Bare land	5880	7.39	4634	5.82	4523	5.68	4472	5.60

Table 4-2 shows the transition matrices that state a LULC class-for-class change from 1988 to 2000 and from 2000 to 2015 in northern Shaanxi. As shown in Table 4-2, the LULC conversion patterns are obviously different before and after implementation of the ERPs. Compared with the ERPs period, all LULC classes showed a stable state in the pre-ERPs period. There was no large-scale LULC transformation in northern Shaanxi during this period. The classes of Woodland, Water bodies, and Built-up land were almost unchanged during this time period. The croplands showed a slight increase from 1988 to 2000, because 435 km^2 of grasslands converted to croplands. However, the grasslands also increased because 1297 km^2 of bare lands converted to grasslands. Thus, the major LULC conversion occurred in grasslands and bare lands during the pre-ERPs period.

However, a dramatic change of the LULC pattern has taken place in northern Shaanxi where the ERPs were carried out from 2000 to 2015. Firstly, the main LULC variation was the decrease in croplands and the increase in woodlands and grasslands in the ERPs period. This conversion is in line with the ERPs objectives, especially in accordance with the objective of converting croplands to forests and grasslands. In particular, 9684 km^2 of croplands converted to grasslands, while 1762 km^2 of croplands converted to woodlands during this period. Secondly, the inter-shifted of LULC occurred in the Cropland, Woodland, and Grassland classes. 7271 km^2 of grasslands also converted to croplands during the ERPs period, while 998 km^2 of woodlands converted to croplands. This result highlighted that the conversion among different LULC types was more complex than the pre-ERPs period.

Table 4- 2 Land use and land cover change matrix in northern Shaanxi (Unit: km^2)

From 1988 to 2000							
	1988						
2000	Cropland	Woodland	Grassland	Water	Built-up land	Bare land	Total
Cropland	27898	28	435	6	0.31	32	28400
Woodland	45	10655	248	0	0.04	36	10984
Grassland	122	123	33120	11	0.17	1297	34673
Water	2	0	4	628	0.02	0	635
Built-up land	29	1	4	0	261	3	298
Bare land	36	2	79	3	0.01	4513	4634
Total	28134	10810	33890	649	262	5880	
From 2000 to 2015							
	2000						
2015	Cropland	Woodland	Grassland	Water	Built-up land	Bare land	Total
Cropland	16276	998	7271	93	88	248	25095
Woodland	1762	8439	1892	18	9	44	12229
Grassland	9684	1386	24301	94	36	647	36167
Water	112	18	97	373	5	19	681
Built-up land	368	44	442	24	155	162	1227
Bare land	156	69	626	10	1	3507	4472
Total	28400	10984	34673	635	298	4634	

Table 4-3 shows the annual change rate of woodland, grassland, and cropland in northern Shaanxi in two different time periods. Compare with two periods, the change rate of woodland, grassland, and cropland were positive during pre-ERPs period, which means these three LULC classes increased. However, the annual change rate of woodland rapidly increased from 0.13/year to 0.72/year after implementation of the ERPs, while the annual change rate of cropland became negative during the ERPs period. The annual change rate of grassland in the ERPs period showed a slight increase compared with pre-ERPs period.

Table 4- 3 Annual change rate of LULC in two different time periods in northern Shaanxi

Annual change rate from 1988 to 2000		
Woodlands (%)	Grasslands (%)	Croplands (%)

+0.13	+0.19	+0.08
Annual change rate from 2000 to 2015		
Woodlands (%)	Grasslands (%)	Croplands (%)
+0.72	+0.28	-0.80

However, the annual change rates of woodland, grassland, and cropland highlighted spatial heterogeneity in different sub-watersheds. Likewise, the annual change rate in different sub-watersheds were spread unevenly. The annual change rates of cropland were positive in the sub-watershed No. 10 and 11, which means croplands in these two sub-watersheds were increase during the ERPs period (Figure 4-1). The annual change rate of cropland in the other 28 sub-watersheds shows different negative level. The lowest change rate of cropland occurred in the sub-watersheds No.18, reached -2.17%/year. Moreover, during the pre-ERPs period, it was found that the annual decreasing rate of cropland ranged from -1%/year to 0, while the annual increasing rate of cropland in many sub-watersheds ranged from 0 to 1%/year. Compared with the ERPs period, the annual change rate of cropland showed a slight increase or decrease tendency during the pre-ERPs period.

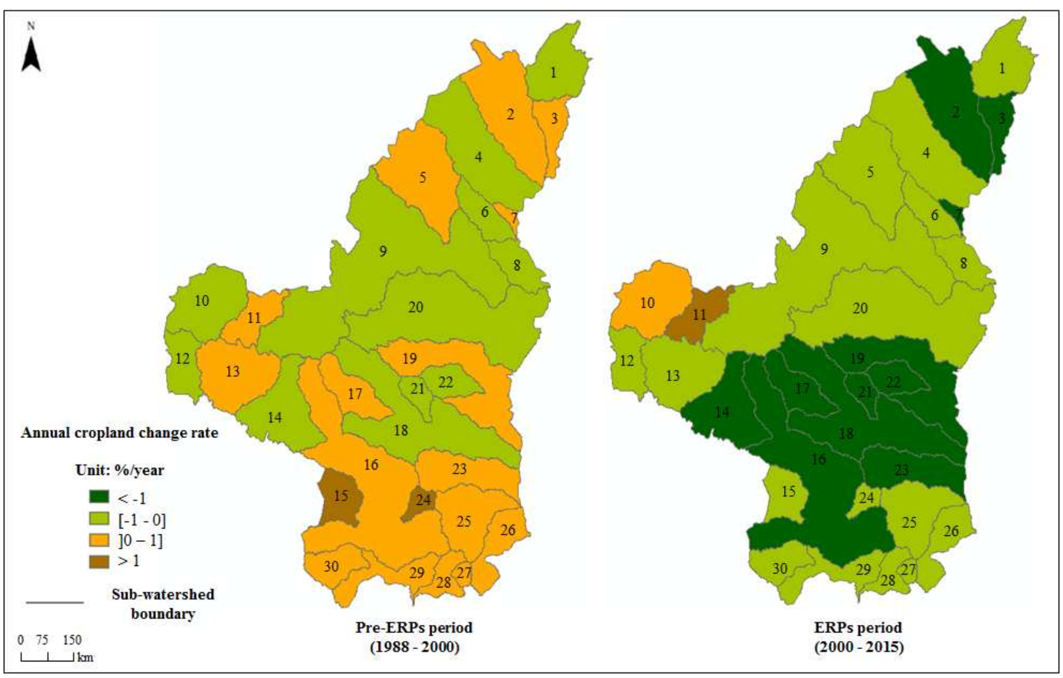

Figure 4- 1 Annual cropland change rate in sub-watersheds before and during ERPs in northern Shaanxi. Sub-watersheds are numbered from 1 to 30.

Figure 4-2 shows the annual change rate of woodland before and after implementation of the ERPs. As for the pre-ERPs period, the change rates of woodland in eleven sub-watersheds were negative, indicating woodlands in these sub-watersheds were decreased during this time period. The change rates of woodland in the rest sub-watersheds were positive, and the change rate ranged from 0 to 2%/year. After the ERPs, there were negative change rates of woodland in sub-watersheds No. 10, 26, and 30, while the change rates of woodland in the rest of sub-watersheds were positive. The positive degree of woodland change rate in many sub-watersheds (e.g. No.1 and 5) in the ERPs period was strengthen compared with the pre-ERPs period. Moreover, it was found that the maximum change rate of woodland was recorded in sub-watershed No.10 during the pre-ERPs period, reached at 2.39%/year. However, it became negative during ERPs period, reached at -0.28%/year which was the minimum change rate of woodland in the ERPs period.

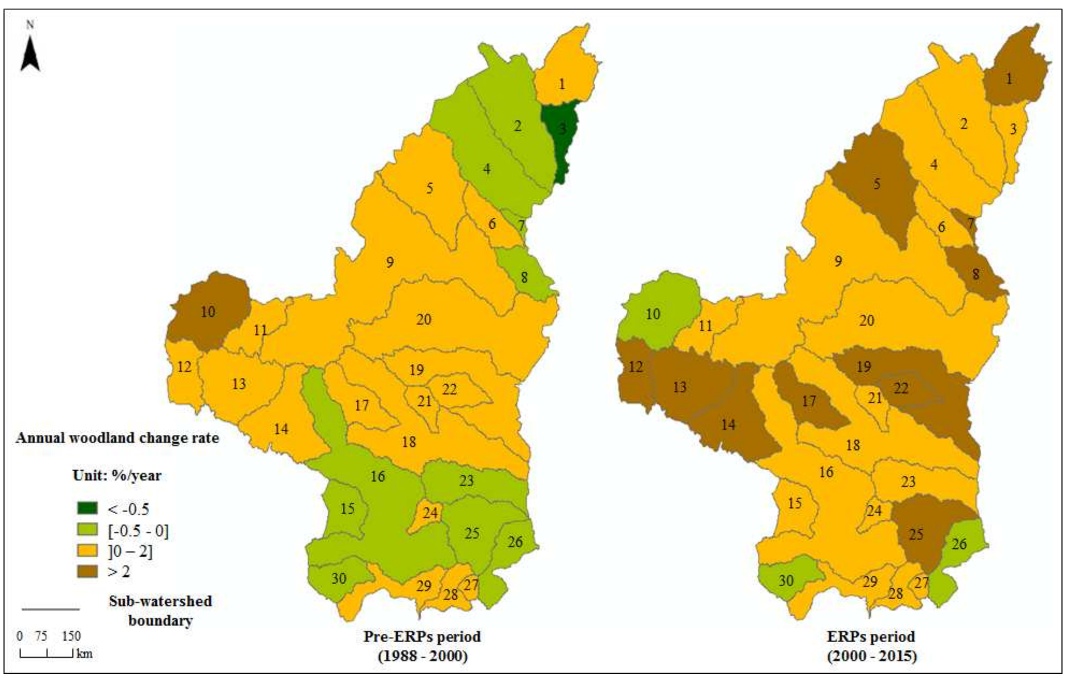

Figure 4- 2 Annual woodland change rate in sub-watersheds before and during ERPs in northern Shaanxi. Sub-watersheds are numbered from 1 to 30.

Figure 4-3 shows the annual change rate of grassland in northern Shaanxi during two time periods. As for the pre-ERPs period, the annual change rates of grassland in most sub-watersheds were negative, and these sub-watersheds were distributed in the south regions.

Sub-watersheds in the north region usually showed a positive annual change rate. As for the ERPs period, most sub-watersheds had positive annual grassland change rate, indicating that grasslands in these sub-watersheds increased after implementation the ERPs. However, the annual change rates of grassland in eight sub-watersheds were still negative during the ERPs period. Moreover, the change rates of grassland in sub-watershed No.1, 10, 15, 29, and 30 were always negative during these two periods, which indicated the grasslands in these regions always decreased.

Before the ERPs, the change rates of grassland in sub-watersheds No. 4 and 5 were strongly positive. The major LULC type in these two sub-watersheds were bare lands, and Table 4-2 shows 1297 km^2 of bare lands converted to grasslands during the pre-ERPs period. This indicated the increased grasslands mainly came from bare lands in these two sub-watersheds. However, the change rate of grassland in sub-watershed No. 5 became negative, which indicated that grasslands in this sub-watershed decreased after implementation of the ERPs.

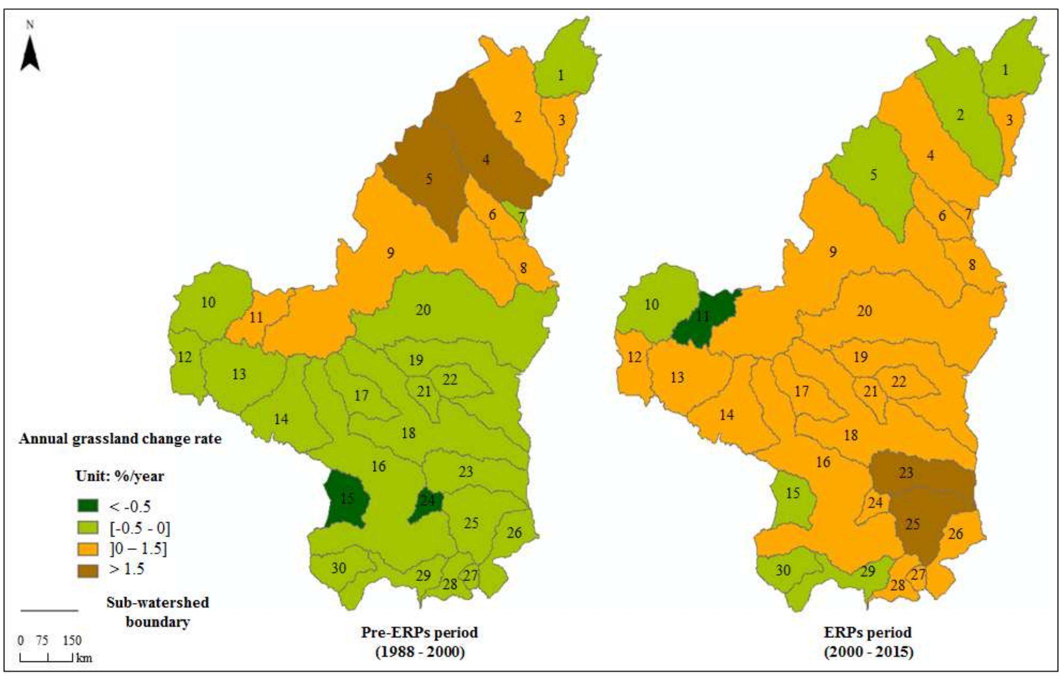

Figure 4- 3 Annual grassland change rate in sub-watersheds before and during ERPs in northern Shaanxi. Sub-watersheds are numbered from 1 to 30.

4.2 LULC spatial change analysis

Figure 4-4 shows the gain and loss of croplands, grasslands, and woodlands in spatial distribution at two different time periods. Firstly, from 1988 to 2000, LULC classes in northern Shaanxi represented a stable status, thus, the spatial conversion of LULC only appeared in particular place. The gains of cropland were observed in the southern regions, while the losses of cropland were found in the west and northwest regions. The gains of woodland were distributed in the central regions, while the losses of woodland were found in the west south regions. The losses of grassland were observed in the central and south regions, while the gains of grassland were found in northern regions.

However, after implementation of the ERPs, the spatial conversion of croplands and grasslands appeared in the whole northern Shaanxi. This is due to croplands and grasslands inter-shift from 2000 to 2015 (Table 4-2). Dramatic gain and loss of Woodland class focused on the central and south study site. This is in line with the LULC change matrix in northern Shaanxi from 2000 to 2015. The large-scale LULC changes appeared in northern Shaanxi. The conversion of croplands, grasslands, and woodlands was more complex compared with the pre-ERPs period.

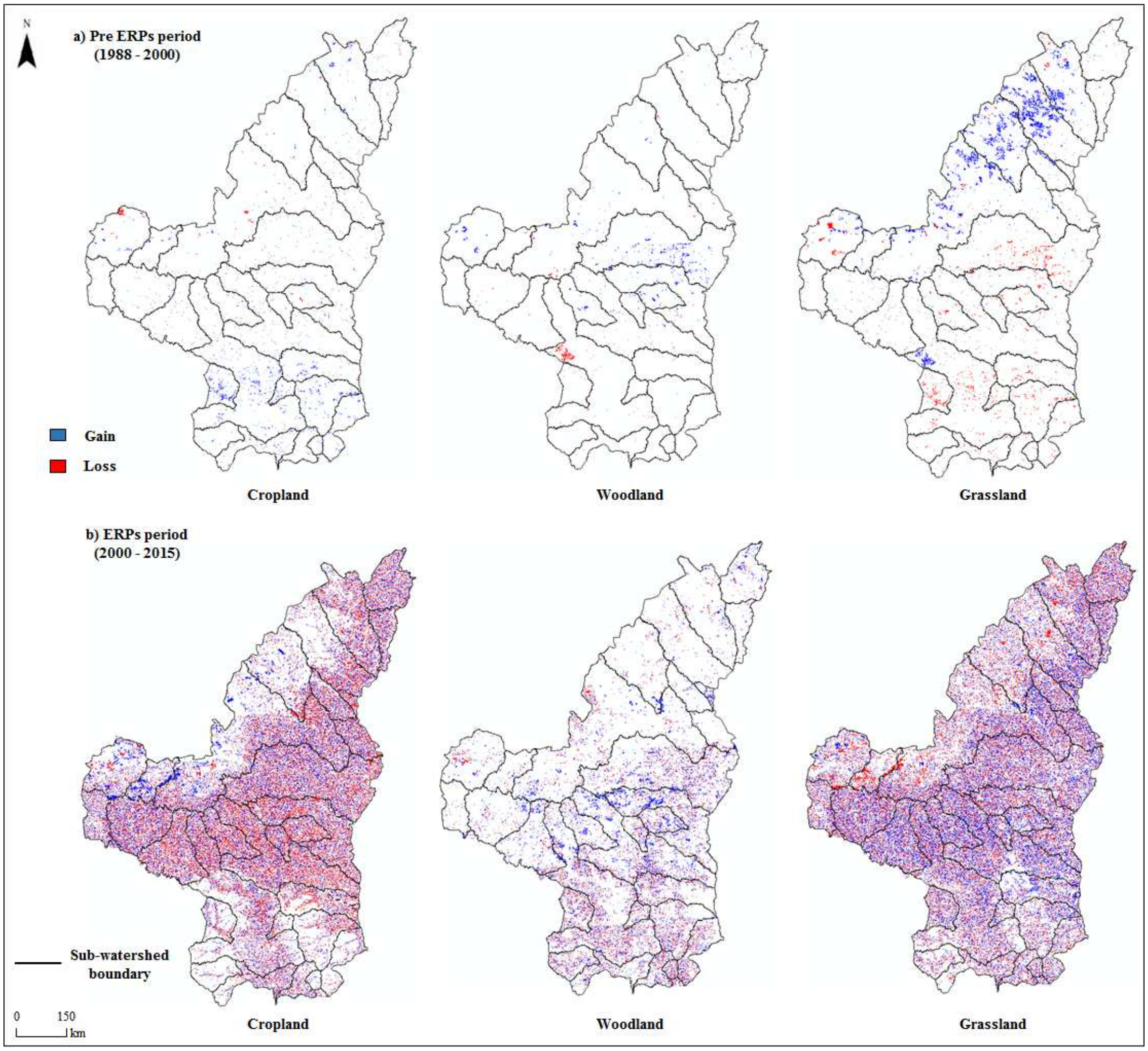

Figure 4- 4 Spatial distribution of gain and loss of cropland, woodland, and grassland before and during ERPs in northern Shaanxi

After implementation of the ERPs, the main LULC change characteristic was the croplands rapid decrease and most of them converted to woodlands and grasslands. We further analysed the spatial conversion of croplands to grasslands and woodlands. From 2000 and 2015, 7121 km^2 of croplands converted to woodlands, while 998 km^2 of croplands converted to grasslands (Table 4-2). As shown in Figure 4-5, the conversion of croplands to grasslands appeared in the whole study site, while the conversion of croplands to woodlands focused on the central regions. In order to increase the vegetation cover, the ERPs converted croplands to woodlands and grasslands, and they conducted afforestation by means of mountain closure, aerial seeding, and artificial planting.

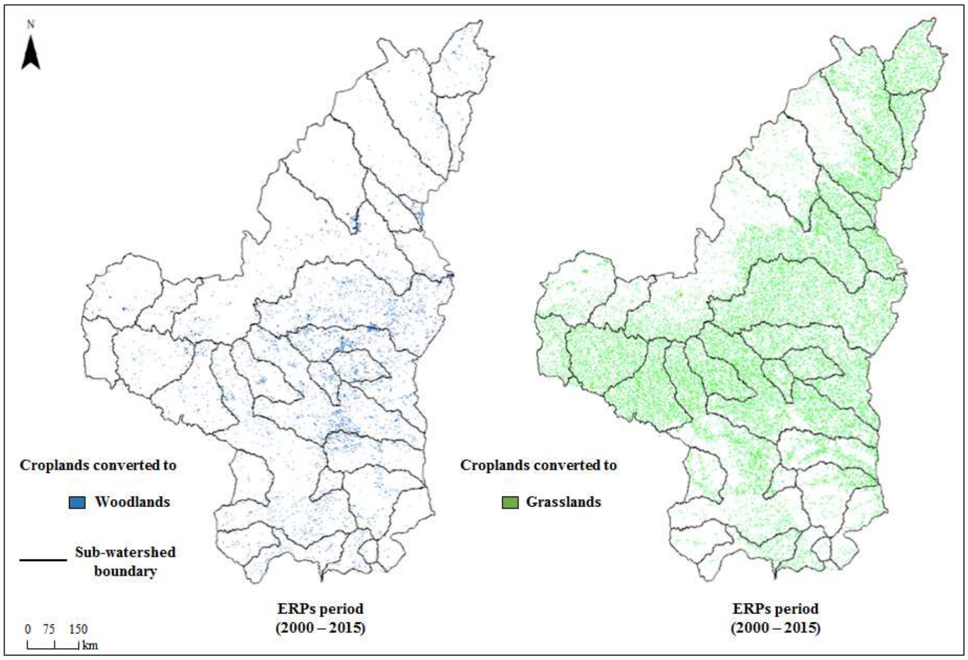

Figure 4- 5 Croplands converted to woodlands and grasslands during the ERPs period in northern Shaanxi

4.3 Discussion

Development of accurate LULC classifications has been an active research topic in recent years (Lu et al., 2013). Great progress in improving LULC classification has been made, such as the development of advanced classification algorithms and multi-source remote sensing data fusion. However, LULC classification is a complex procedure, the results of which may be affected by many factors such as the study site characteristics, data sources, classification algorithms, and the analyst's experience. Misclassification often occurred due to the complex biophysical environments resulting in similar spectral or radiometric data and the constraint of remote sensing data and techniques (Lu and Weng 2007). The LULC classification maps used in this study were obtained from the DCRES, CAS. At the national scale, Landsat images were used to examine LULC dynamic changes in China (Liu et al., 2005). It usually takes much time and labor cost to finish this work. Coarse spatial resolution images become a primary data source at national LULC change detections. For the classification validation, the CAS usually conducted a field survey to evaluate the classification accuracy. In this study, the research objective is to analyse the

LULC changes on water-related ES on a regional scale. The LULC classification maps provided by the DCRES, CAS was satisfying for our study.

There have been dramatic LULC changes in northern Shaanxi from 1988 to 2015, especially after the ERPs were launched. Our results indicated that the major characteristic of LULC change in northern Shaanxi from 2000 to 2015 is croplands decreased while vegetation areas, included woodlands and grassland, rapidly increased. This LULC change tendency is in line with Jia et al. (2014), Zhen et al. (2014) and Wei et al. (2017). Secondly, our results found that grasslands rapidly increased compared with woodlands during the ERPs period. This is because that croplands were more likely converted to grasslands. Thirdly, the inter-shifted of LULC occurred in the Cropland, Woodland, and Grassland classes after implementation of the ERPs. Especially the inter-shifted of LULC existed between croplands and grasslands, which led to the cropland and grassland losses and gains occurred in the whole study site during ERPs period.

Moreover, our results indicated that the annual change rates of woodland, grassland, and cropland highlighted spatial heterogeneity in different sub-watersheds. The croplands did not always decrease in all sub-watersheds even after implementation of the ERPs while the grasslands and woodlands did not always increase in all sub-watersheds. Cao et al. (2010) investigated the impacts of the ERPs on the livelihoods of residents in northern Shaanxi. Their results indicated that 34.9%, 47.0%, and 59.8% of farmers, livestock grazers, and forest workers, respectively, in Northern Shaanxi Province believed that their livelihoods had been adversely affected by the ERPs. They perceived additional economic losses because they were not adequately compensated for their economic losses under the programs. This might be one of the reasons why the ERPs implemented less successful in some sub-watersheds.

These large-scale LULC conversions apparently appeared in 2000, implying that the ERPs played an important role in LULC decision making. However, LULC changes are usually caused by multiple driving forces. The impacts of social and economic factors on LULC changes cannot be ignored. Firstly, the rapid economic development is often correlated with the increase of population size for the same periods (Fischer et al., 1997). Population growth has long been considered a major factor leading to LULC changes (Ho and Lin, 2004). In northern Shaanxi, the population and GDP showed an increase tendency from 1988 to 2013 (Figure 3-11). A Pearson's correlation analysis made between population and GDP from 1988 to 2013 showed that the population increase was strongly positively correlated with GDP (Correlation coefficient = 0.96, significant at the 0.01 level). Secondly, China's urbanization growth has been at an unprecedented speed. In the period 2000–2015, the fraction of China's population dwelling in cities increased from 36.2% to 56.1% (China Statistical Yearbooks, 2001, 2016). If the current trend holds, China's urban population is estimated to top 1 billion people in the next two decades (Bai et al., 2014). In northern Shaanxi, built-up lands rapidly increased from 298 km^2 in 2000 to 1227 km^2 in 2015. In particular, 368 km^2 of croplands and 442 km^2 of grasslands converted to built-up lands from 2000 to 2015. Thus, the social-economic factors which include the population, urbanization, and economy can affect LULC changes in northern Shaanxi.

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Chapter 5 Water-related ecosystem service analysis

Summary

In this Chapter, details regarding the temporal and spatial water-related ES changes in northern Shaanxi in the pre-ERPs (1988-2000) and ERPs (2000-2015) periods are presented. The major findings are as follows:

1) Water-related ES changes from 1988 to 2015 showed both soil erosion and water yield decrease in the whole study site. However, soil erosion and water yield rapidly decreased in the ERPs period in comparison to the pre-ERPs period.
2) The change rate of soil erosion varied from one sub-watershed to another. Three sub-watersheds showed an increasing annual change rate, while the rest of sub-watersheds showed a decreasing annual change rate during the ERPs period.
3) As for the change rate of water yield, spatial heterogeneity existed in different sub-watersheds during the pre-ERPs period. Before the implementation of the ERPs, the change rates of water yield in five sub-watersheds were positive, indicating that water yield increased from 1988 to 2000. However, since 2000, the change rates of water yield are negative in all sub-watersheds, indicating that water yield in all sub-watersheds decreased during the ERPs period. In particular, sub-watersheds located in the central and western regions showed a strong annual decrease with a rate of -3%/year.

Résumé

Dans ce chapitre, les détails concernant les changements temporels et spatiaux des SE liés à l’eau dans le nord du Shaanxi pendant les périodes pré-PRE (1988-2000) et PRE (2000-2015) sont présentés. Les principales conclusions sont les suivantes :

1) Les changements de SE liés à l’eau entre 1988 et 2015 ont montré une diminution de l’érosion des sols et de l’apport en eau dans l’ensemble du site d’étude. Cependant, l’érosion du sol et l’apport en eau ont rapidement diminué pendant la période des PRE par rapport à la période pré-PRE.
2) Le taux de changement de l’érosion du sol varie d’un sous-bassin versant à l’autre. Trois sous-bassins versants affichaient un taux de changement annuel croissant,

alors que le reste des sous-bassins présentait un taux de changement annuel décroissant au cours de la période des PRE.

3) En ce qui concerne le taux de changement de l'apport en eau, une hétérogénéité spatiale est observée dans différents sous-bassins versants pendant la période pré-PRE. Avant la mise en œuvre des PRE, les taux de changement de l'apport en eau dans cinq sous-bassins sont positifs, indiquant une augmentation de 1988 à 2000. Cependant, depuis 2000, les taux de changement sont négatifs dans tous les sous-bassins, indiquant que l'apport en eau a diminué pendant la période des PRE. En particulier, les sous-bassins versants situés dans les régions du centre et de l'ouest ont enregistré une forte baisse annuelle avec un taux de -3% / an.

5.1 Spatiotemporal changes of soil erosion in northern Shaanxi

5.1.1 Pixel-based scale analysis of soil erosion

Table 5-1 shows the annual soil erosion for the years of 1988, 2000, 2008, and 2015. Soil erosion showed a decrease tendency from 1988 to 2015 in northern Shaanxi. The annual soil erosion in northern Shaanxi decreased from 1.21 billion tonnes in 1988 to 0.77 billion tonnes in 2015. However, compared with the pre-ERPs period, annual soil erosion rapidly decreased during the ERPs period. Moreover, the average soil loss rate also dropped to 9766 t km^{-2} yr^{-1} in 2015, ranking the lowest in the assessed period. While in 2000, it was 13846 t km^{-2} yr^{-1}, and 15386 t km^{-2} yr^{-1} in 1988.

Table 5- 1 The annual soil erosion from 1988 to 2015 in northern Shaanxi

Water-related ES	**Year**			
	1988	**2000**	**2008**	**2015**
Soil erosion (billion tonnes)	1.21	1.09	0.98	0.77
Average soil loss rate (t km^{-2} yr^{-1})	15386	13846	12523	9766

Table 5-2 shows the annual soil erosion change rate in the whole study site before and after implementation of the ERPs. The annual change rates of soil erosion in both pre-ERPs and ERPs periods were negative, indicating the amount of soil erosion in northern Shaanxi always decreased. Compare with the pre-ERPs, the annual change rate of soil erosion in the ERPs period was higher indicating that soil erosion decrease strengthened after the implementation of the ERPs.

Table 5- 2 The annual soil erosion change rate before and after ERPs in northern Shaanxi

	Pre-ERPs (%)	**ERPs (%)**
Annual soil erosion change rate	-0.8/year	-1.9/year

The spatial distribution of soil erosion levels for four years are given in Figure 5-1. The results indicated that there were significant spatial variations of soil erosion during the study periods. As shown in Figure 5-1 and Figure 5-2, most of soil erosion changes occurred at severe soil erosion level. Severe soil erosion was observed in the central and north regions in 1988, taking up 53% of the total area. In 2000, it still occurred mainly in the central and north regions, while severe soil erosion areas decreased to 41%. In 2015, areas of severe soil erosion rapidly decreased to 15% and most of them were distributed in the west and northwest regions. However, an area of severe soil erosion appeared in the southwest in 2015, while soil erosion level in this region was very intensive in 2000.

Areas of very intensive soil erosion was mainly distributed in the west regions in 1988, while it expanded into the east regions in 2000. In 2015, it further expanded into the central regions. As shown in Figure 5-2, areas of very intensive increased from 1988 to 2008, while it decreased from 2008 to 2015. Areas of intensive soil erosion always increased from 1988 to 2015, especially rapidly increased from the period of 2008-2015s. The changes of intensive soil erosion appeared in the south regions. In 1988, soil erosion was mainly severe level in this region, while intensive level of soil erosion only accounted for a small region. However, soil erosion level in this region became intensive in 2015, indicating that soil erosion rapidly decreased in south regions. Moreover, areas of slight, light, and moderate soil erosion were small compared with the area of very intensive and severe soil erosion in northern Shaanxi.

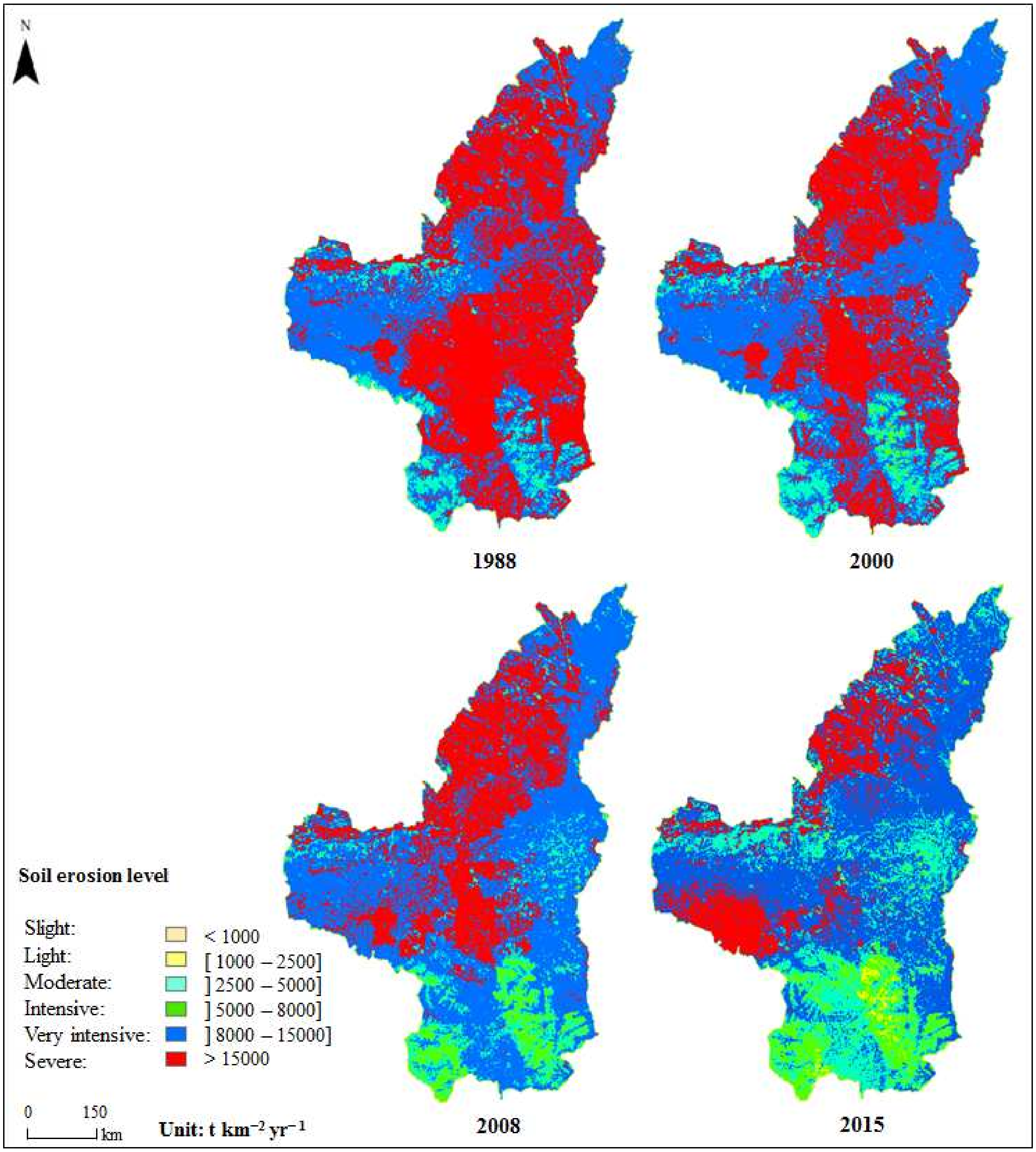

Figure 5- 1 Spatial distribution of soil erosion in northern Shaanxi from 1988 to 2015

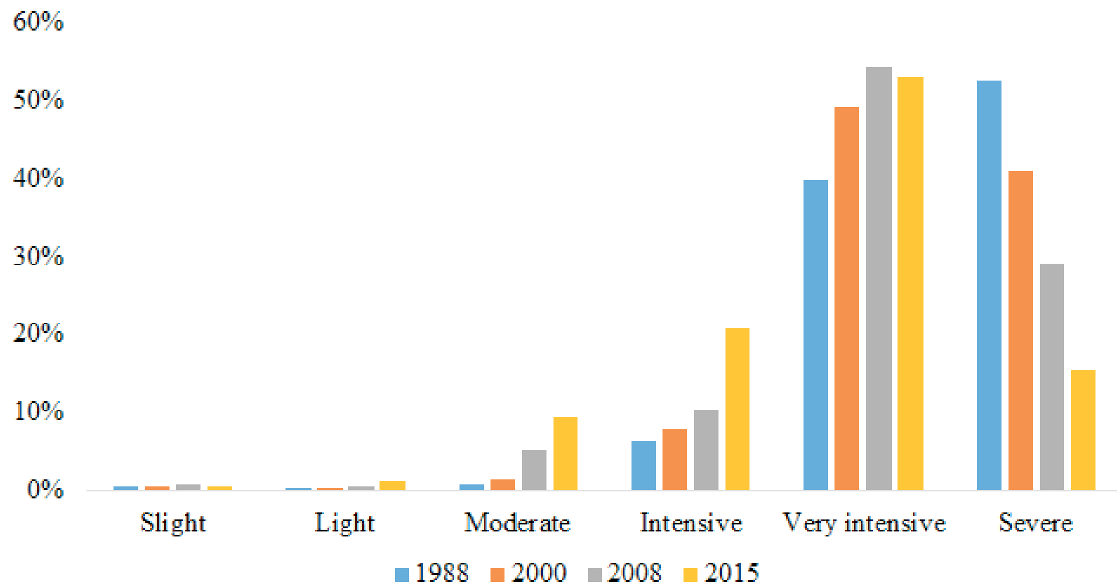

Figure 5- 2 Percentage of soil erosion level in northern Shaanxi from 1988 to 2015

Figure 5-3 summarizes the results for the soil erosion on each LULC type in 1988, 2000, 2008, and 2015. The contribution of soil erosion on each LULC type was significantly different. Except the built-up land, the amount of soil erosion on the other LULC types decreased from 1988 to 2015, and the estimates of total soil erosion mainly come from croplands, moderate grasslands, and sparse grasslands. Soil erosion coming from croplands in 1988 was 371 million tonnes, accounting for 30% of total soil erosion, while it was 208 million tonnes in 2015, account in for 27% of total soil erosion. Soil erosion coming from moderate grasslands in 1988 and 2015 was 310 million tonnes (25%) and 209 million tonnes (27%) respectively. Soil erosion coming from sparse grasslands was 256 million tonnes (21%) for 1988, while it was 174 million tonnes (23%) for 2015. However, after implementation of the ERPs, soil erosion coming from croplands and sparse grasslands rapidly decreased in comparison to pre-ERPs period. The total amount of soil erosion estimated from croplands decreased by 128 million tonnes from 2000 to 2015, while it only decreased by 35 million tonnes from 1988 to 2000. Soil erosion estimated from sparse grasslands decreased by 74 million tonnes during ERPs period, while it decreased by 8 million tonnes during pre-ERPs period.

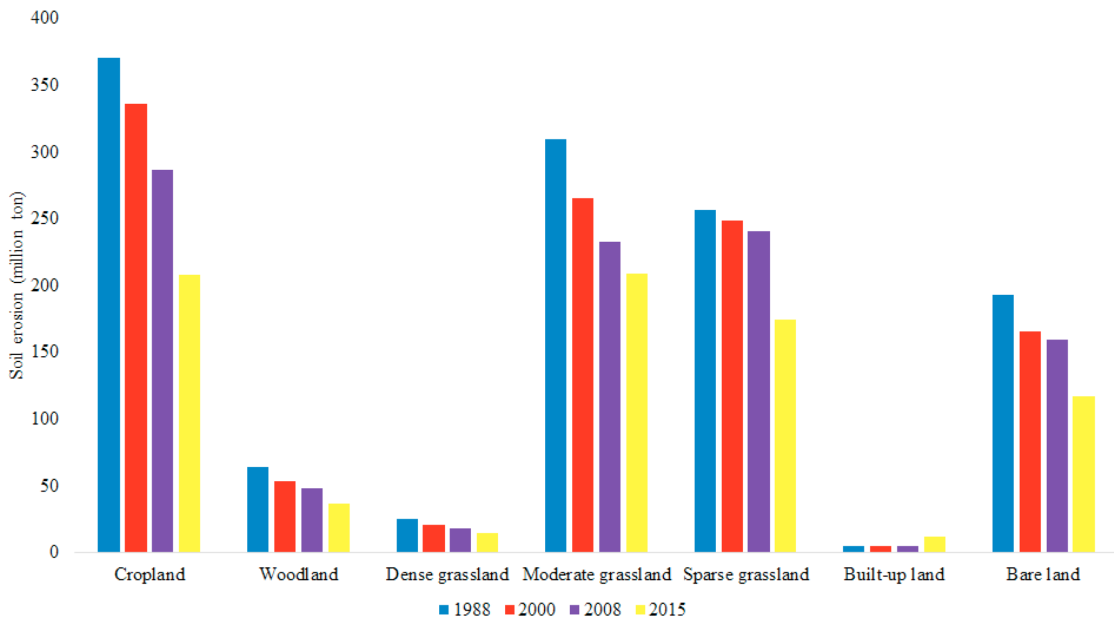

Figure 5- 3 Total amount of soil erosion estimated from different LULC types from 1988 to 2015

5.1.2 Sub-watershed scale analysis of soil erosion

We further analysed the annual soil erosion change rate in different sub-watersheds in northern Shaanxi. Annual change rates of soil erosion highlighted spatial heterogeneity in different sub-watersheds.. As shown in Figure 5-4, the change rates of soil erosion in sub-watersheds No. 5, 9 and 29 were positive during the pre-ERPs period. It was also positive during the ERPs period in sub-watersheds No. 12, 13 and 14 which means that annual soil erosion increased in these sub-watersheds after implementation of ERP's while it showed a decreased tendency in the pre-ERPs period. In contrast, compared with pre-ERPs period, soil erosion in sub-watersheds No. 5, 9 and 29 decreased during the ERPs period. Secondly, the annual changes rates of soil erosion in most of sub-watersheds were negative, which means soil erosion in these sub-watersheds decreased from 1988 to 2015. However, the annual change rate of soil erosion in the ERPs period were further enhanced compared with the pre-ERPs period. For example, the annual change rate of soil erosion in sub-watershed No. 1 was -0.4%/year in the pre-ERPs period while it became -2.43%/year in the ERPs period.

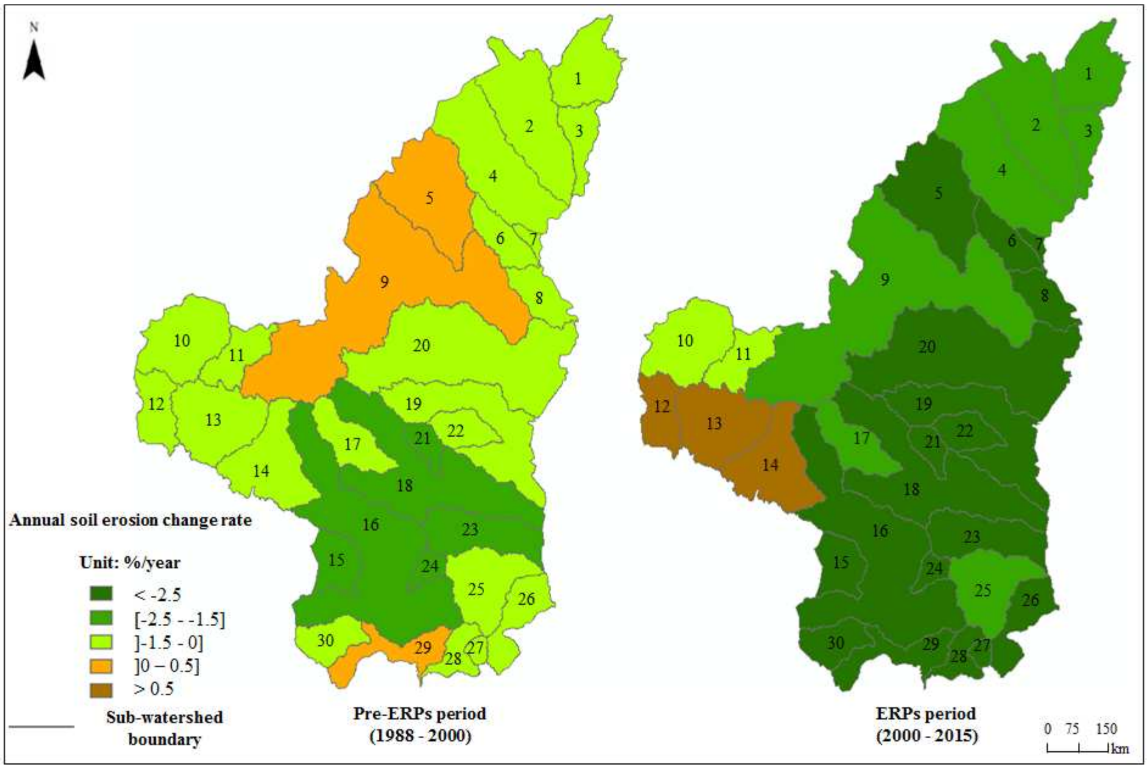

Figure 5- 4 Annual soil erosion change rate in sub-watersheds before and during ERPs in northern Shaanxi. Sub-watersheds are numbered from 1 to 30.

5.2 Spatiotemporal changes of water yield in northern Shaanxi

5.2.1 Water yield changes at the sub-watershed scale

The average water yield among thirty sub-watersheds decreased from 1988 to 2015 (Table 5-3). Water yield showed a decreased tendency from 1988 to 2015 in northern Shaanxi. The lowest average water yield appeared in 2015 (5.86 billion m^3), while the highest appeared in 1988 (13.75 billion m^3). Compared with the pre-ERPs period, water yield rapidly decreased during the ERPs period, decreased by 4.88 billion m^3.

Table 5- 3 The average water yield among thirty sub-watersheds in northern Shaanxi from 1988 to 2015

	Year			
	1988	**2000**	**2008**	**2015**
The average water yield among thirty sub-watershed (billion m^3)	13.75	10.74	7.26	5.86

Table 5-4 shows the annual water yield change rate before and after implementation of the ERPs. The results indicated the change rate in both time period was negative, which indicates that the amount of water yield among thirty sub-watersheds always decreased. But the annual decreasing rate of water yield was strengthened after implementation of the ERPs, reaching -3%/year.

Table 5- 4 The annual water yield change rate before and after ERPs in northern Shaanxi

	Pre-ERPs (%)	**ERPs (%)**
Annual water yield change rate	-2.3/year	-3.0/year

Figure 5-5 shows the spatial distribution of water yield in four different years in northern Shaanxi. The results indicate that the average water yield significantly varied from one sub-watershed to another from 1988 to 2015. Apart from sub-watersheds No. 10, 11, 12, 13, and 14, the highest value of water yield in all sub-watersheds appeared in 1988, while the lowest value of water yield in all sub-watersheds appeared in 2015. For example, average water yield in sub-watershed No. 17 was 0.21 billion m^3 in 1988, while it was 0.09 billion m^3 in 2015. The average water yield in most sub-watersheds represented a decreased tendency from 1988 to 2015. Secondly, the highest water yield areas came from No.16 watershed during 1988 to 2015. The amount of water yield in this sub-watershed showed a strongly decreased tendency, decreased from 2.12 billion m^3 in 1988 to 0.91 billion m^3 in 2015. The lowest value of this service was found in No. 7 sub-watershed. The amount of water yield in this sub-watershed showed a slightly decreased tendency, decreased from 0.04 billion m^3 in 1988 to 0.02 billion m^3 in 2015.

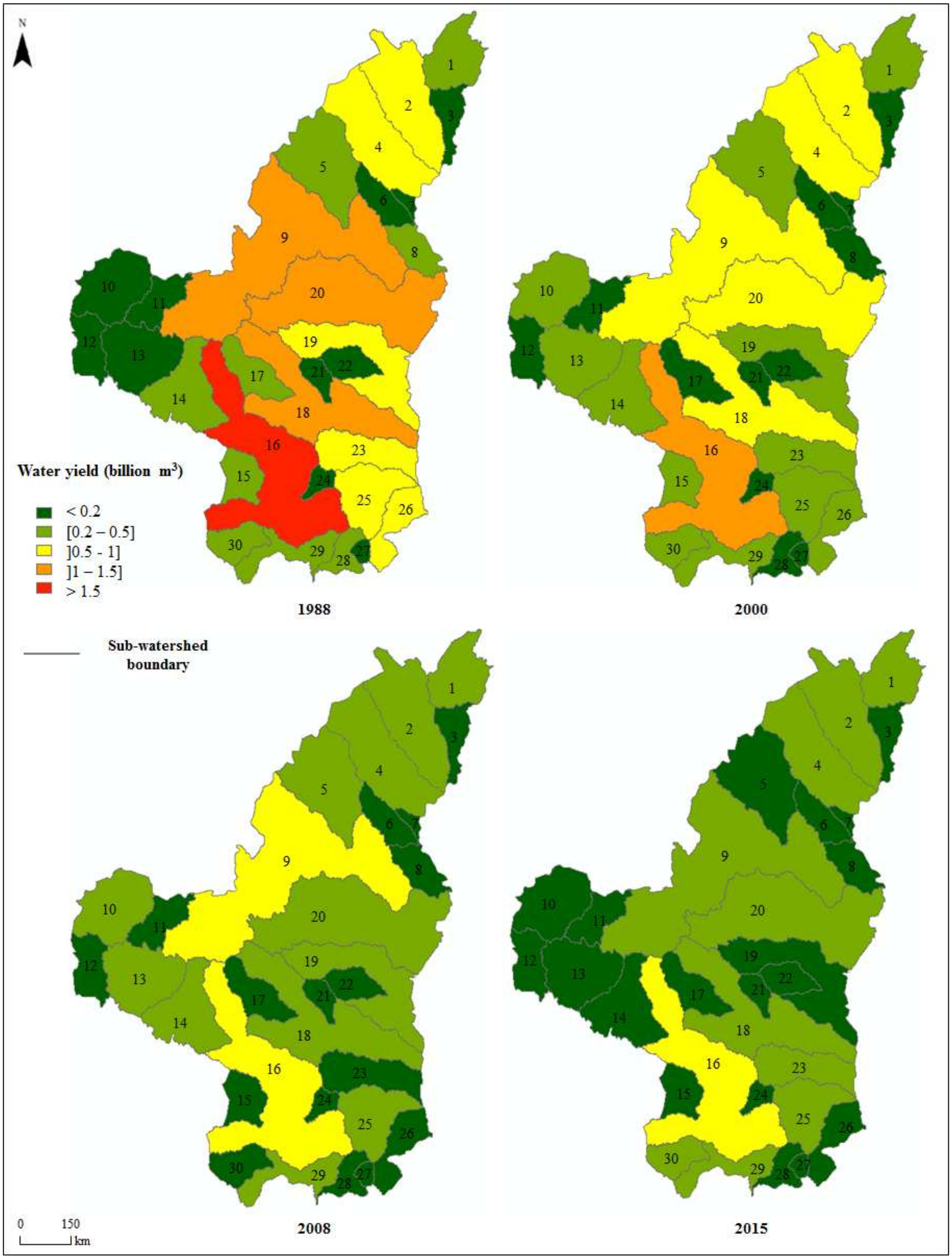

Figure 5- 5 Spatial distribution of water yield at the sub-watershed in northern Shaanxi. Sub-watersheds are numbered from 1 to 30.

5.2.2 Annual water yield change rate at the sub-watershed scale

As shown in Figure 5-6, the annual change rate of water yield showed spatial heterogeneity during the pre-ERPs period. Before implementation of the ERPs, the annual water yield change rate in sub-watersheds No. 10 to 14 was positive, which indicates that water yield in these five sub-watersheds increased. Change rate of water yield in seven sub-watersheds showed a strong negative change rate (<-3%/year) and five of them were distributed on the southeast region. After implementation of the ERPs, the annual water yield change rate in all sub-watersheds was negative, which indicates that water yield in all sub-watersheds decreased during the ERPs period. The sub-watersheds which are located in the west and central region showed a strong negative change rate (<-3%/year).

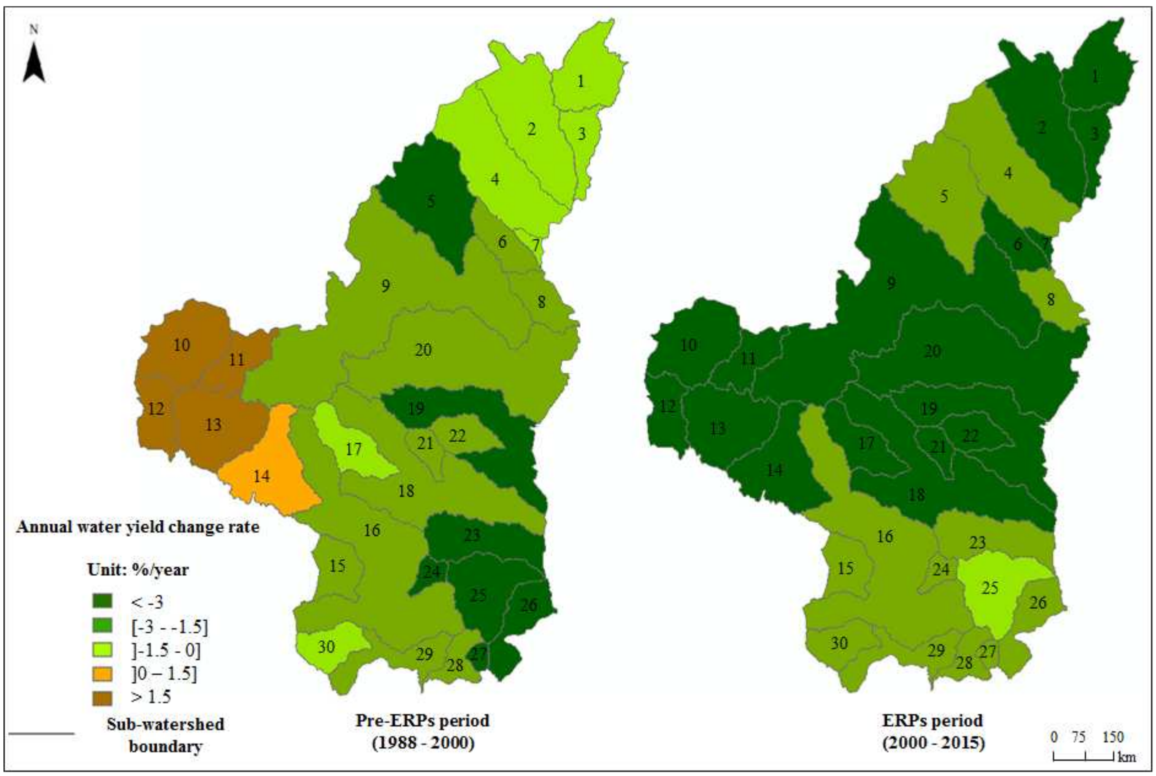

Figure 5- 6 Water yield change rates in sub-watersheds before and after ERPs in northern Shaanxi. Sub-watersheds are numbered from 1 to 30.

5.3 Discussion

5.3.1 Water-related ES changes in northern Shaanxi

In this chapter, we provided empirical evidence that the total supply of water-related ES varied under ecological restoration. It was found that both the amount of soil erosion and water yield rapidly decreased during the ERPs period. Although the validation of ES simulation results estimated at large temporal-spatial scales is rather problematic due to the lack of observation data at large spatial and long-term temporal scales (Schulp et al., 2014), similar results were reported by Jia et al. (2014) who stated that both soil erosion and water yield exhibited overall decreased after the implementation of the ERPs in northern Shaanxi from 2000 to 2008. Likewise, our study site is located in the middle of the Loess Plateau which is known for its fertile and highly erodible land. Thus, we compared our results with the newest available data for water-related ES in the Loess Plateau and the integrated national ecological maps produced from national programs. Our results are in line with Fu et al. (2011), Wang et al. (2011), Su and Fu (2013), Li et al. (2016) who reported that while the ERPs decreased soil erosion in Loess Plateau, water yield was also reduced. Moreover, our results are also in line with Cao (2008), Cao et al. (2016), Liu et al. (2016) and Lu et al. (2016) who pointed out that surface water yield decreased due to large-scale afforestation in arid and semiarid regions in China.

5.3.2 Multiple temporal and spatial ES analysis

The provision of ES can be affected by different social-ecological processes, which means that the distribution of benefits and the management of ES may occur at particular scales. Interactions between some ES may be observable at some scales and not others, and information generated at particular scales may or may not be usable by managers acting at other scales (Raudsepp-Hearne and Peterson, 2016). Previous studies indicated that massive planted trees in the Loess Plateau altered hydrologic cycles (Cao et al., 2011). Water availability in the Loess Plateau appeared to be unsuitable for afforestation using current tree species, because these trees commonly consumed huge volumes of water compared with native grassland and plants (Feng et al., 2012). Thus, the implementation of ERPs in these regions might become unstable and actually degrade ecological functions. As a part of the Loess Plateau, water is one of the most important factors for large-scale afforestation and social economic development in northern Shaanxi. One of the ERPs purpose in this region was to reduce soil erosion. In this study, the newest LULC map (2015) provided by the government-maintained monitoring infrastructure- Chinese Academy of Sciences was used. The results indicated that spatial heterogeneity existed in different sub-watersheds. Although the annual soil erosion and the amount of annual water yield decreased in the whole study site, the amount of soil erosion in some sub-watersheds increased after implementation of the ERPs, indicating that the ERPs might not always help reduce the risk of soil erosion in northern Shaanxi. This result also suggests that the current level of the ERPs might need to be modified in northern Shaanxi. Chapter 6 is to analyse relationships between LULC changes and soil erosion and water yield at sub-watershed scale in details.

5.3.3 Uncertainties of ES modeling

Although the USLE has been widely used for predicting soil erosion on agricultural fields in China, the most effective use of the USLE requires that regional values for each parameter be developed based on local data and conditions (Wischmeier, 1978). Five parameters are included in the USLE. In this study, the methods for calculating each parameter were based on the previous studies which have been successfully used in the Loess Plateau (Chapter 3). However, spatial distribution of rainfall erovisity maps were derived from the weather stations which are observations from field experiments at small spatial scales. These sample field experiment data were used to represent the rainfall erovisity at a regional scale through interpolation tools, which might affect the USLE model accuracy. Moreover, vegetation cover is considered as one of the most important parameters in this study, while reference *C* values were assigned to the main LULC types which were derived from the satellite images. The uncertainties from the LULC classification maps may affect the accuracy of the USLE simulation results.

The InVEST water yield model is based on the Budyko curve and annual average precipitation. Precipitation data was obtained from weather stations in this study, then these sample collection data represented precipitation in a regional scale through interpolation tools, which might affect the InVEST water yield model accuracy. Moreover, ET_0 links with both water and energy balances, which plays an important role in the climate-soil-vegetation interactions (Milly 1994). The FAO Penman-Monteith method has been considered as a universal standard to estimate ET_0 for more than a decade (Allen et al., 1998). However, due to the lack of meteorological data (e.g. wind speed at 2m height), HS method was employed to calculate ET_0 in this study. Although HS model has been widely used for calculating ET_0 in semi-arid and arid regions (e.g. Zhao et al., 2004; Luo et al., 2014), it is a mathematical-based method, and no physical basis of evapotranspiration processes is taken into account, which might affect the InVEST water yield model accuracy.

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Chapter 6 Relationship analysis

Summary

This chapter analyses impacts of ERPs on soil erosion and water yield, and the potential factors leading to spatial heterogeneity between LULC and water-related ES in northern Shaanxi. Finally, the relationships between soil erosion and water yield are analysed.

The major findings in this Chapter are listed as follows:

1. Large-scale LULC changes caused by the ERPs implementation in northern Shaanxi affected the changes of water-related ES. However, relationships among LULC, soil erosion, and water yield varied from one sub-watershed to another. These results suggested that the ERPs implemented in northern Shaanxi might not always help soil and water conservation.
2. As for soil erosion, 95% of the study area showed a positive relationship between croplands and soil erosion, indicating that higher cropland increase is linked to higher soil erosion increase. In other words, decreasing cropland areas can help reduce the risk of soil erosion. Moreover, the negative relationships between woodland/grassland and soil erosion only existed in most north sub-watersheds, indicating that increase of woodlands and grasslands in most north sub-watersheds can help reduce the risk of soil erosion. Thus, implementation of the ERPs in northern regions in the study site can help reduce the risk of soil erosion.
3. As for water yield, 65% of the study area (twenty-one sub-watersheds) showed a negative relationship between woodlands and water yield, while 40% of the study area (nine sub-watersheds) presented a negative relationship between grasslands and water yield after implementation of the ERPs. These results indicated that the increase of woodlands and grasslands can decrease water yield in most sub-watersheds in northern Shaanxi.
4. It was found that trade-offs existed in soil erosion and water yield, which means that an improvement in erosion service is achieved at the expense of a decrease in the provision of water in northern Shaanxi.

Résumé

Ce chapitre analyse les impacts des PRE sur l'érosion des sols et l'apport en eau, ainsi que les facteurs potentiels conduisant à l'hétérogénéité spatiale entre les classes d'occupation du sol et les SE liés à l'eau dans le nord du Shaanxi. Enfin, les relations entre l'érosion du sol et l'apport en eau sont analysées.

Les principales conclusions de ce chapitre sont énumérées comme suit :

1) Les changements d'occupation du sol à grande échelle provoqués par la mise en place des PRE dans le nord du Shaanxi ont affecté les changements des SE liés à l'eau. Cependant, les relations entre l'occupation du sol, l'érosion des sols et l'apport en eau varient d'un sous-bassin versant à l'autre. Ces résultats suggèrent que les PRE mis en place dans le nord du Shaanxi pourraient ne pas toujours aider à la conservation des sols et de l'eau.
2) En ce qui concerne l'érosion des sols, 95% de la superficie a montré une relation positive, ce qui indique que l'augmentation des terres cultivées est liée à une augmentation de l'érosion du sol. En d'autres termes, la diminution des surfaces cultivées peut aider à réduire le risque d'érosion des sols. De plus, les relations négatives entre les terres boisées et les prairies et l'érosion des sols n'existaient que dans la plupart des sous-bassins versants du nord, ce qui indique que l'augmentation des terres boisées et des prairies dans la plupart des sous-bassins versants pourrait réduire le risque d'érosion. Ainsi, la mise en œuvre des ERP dans les régions septentrionales du site d'étude peut aider à réduire le risque d'érosion des sols.
3) En ce qui concerne l'apport en eau, 65% de la zone d'étude (vingt et un sous bassins) présentent une relation négative entre les zones boisées et l'apport en eau, tandis que 40% de la zone d'étude (neuf sous-bassins) présentent une relation négative entre les prairies et l'apport en eau après la mise en œuvre des PRE. Ces résultats indiquent que l'augmentation des terres boisées et des prairies peut réduire l'apport en eau dans la plupart des sous-bassins versants du nord du Shaanxi.
4) Il a été constaté qu'il existait des compromis entre l'érosion du sol et l'apport en eau, ce qui signifie qu'une amélioration du service de l'érosion est obtenue au détriment d'une diminution de l'approvisionnement en eau dans le nord du Shaanxi.

6.1 Impacts of LULC changes on water-related ES

This section firstly assessed the GWR model used to analyse the relationships between LULC and water-related ES at sub-watershed scales through comparing this model performance with OLS. Then, the relationships between soil erosion and LULC and between water yield and LULC is analysed.

6.1.1 The GWR model assessment

The comparison of adjusted R^2, *AICc* and Residuals′ Moran′s *I* between GWR and OLS is displayed in Table 6-1. Firstly, compared with OLS, a dramatic improvement in adjust R^2 is observed for every pair of soil erosion and LULC types and every pair of water yield and LULC types in GWR model. All adjusted R^2 values in GWR are more than 0.50. For the pre-ERPs period, the adjusted R^2 values for the models of soil erosion and LULC types are improved from the values of -0.03 to 0.17 for OLS to the values of 0.53 to 0.63 for GWR. The adjusted R^2 values for the models of water yield and LULC types are also improved from the values of -0.03 to 0.06 for OLS to the values of 0.84 to 0.89 for GWR. For the ERPs period, all adjusted R^2 values for the GWR model are higher than the adjusted R^2 values in the OLS model. Such results indicated an improvement in the model performance using GWR.

Secondly, comparisons of the *AICc* values from the two models with the same independent variable provide a relatively simple way to decide the better model. According to Table 6-1, all *AICc* values for the GWR model are lower than the *AICc* values in the OLS model. Smaller values of *AICc* indicate a better performance of the models. This suggests that, based on the *AICc*, GWR is better than OLS for analyzing the impacts of LULC changes on water-related ES in northern Shaanxi.

The results of Moran's *I* on the residuals from OLS and GWR models are also shown in Table 6-1. Moran's *I* is commonly used as an indicator of spatial autocorrelation, and its values range from −1 to 1. The larger the absolute value of Moran's *I is*, the more significant the spatial autocorrelation. Statistically significant clustering of high or low residuals indicates that at least one key explanatory variable, which could effectively capture the inherent spatial structure in the dependent variable, is missing from the model (Gao and Li, 2011). In other words, the residuals shouldn't be spatially auto-correlated. As shown in Table 6-1, significant positive spatial autocorrelations are found for all the OLS models in three LULC variables for the ERPs periods. In contrast, all the corresponding GWR models for three LULC variables in the ERPs period have no significant spatial autocorrelations in their residuals. This result indicates that these OLS models are unsuitable for identifying the relationships between LULC and water-related ES in the ERPs period as the OLS assumption of residual independence is not met.

However, in the pre-ERPs period, significant positive spatial autocorrelations are found for all the OLS models, characterized by Moran's *I* ranging from 0.37 to 0.67, and most GWR models, characterized by Moran's *I* ranging from 0.16 to 0.37. This result indicates that the GWR models produced smaller global Moran's *I* than OLS models with the same independent variable, indicating that GWR models improve the reliability of the relationships by reducing the spatial autocorrelations in residuals.

Table 6- 1 Comparison of R^2, *AICc*, and residuals' Moran's I from GWR and OLS models

Water-related ES	**LULC**	**Model**	**Adjust R^2**		***AICc***		**Residuals′ Moran′s *I****	
			Pre-ERPs	ERPs	Pre-ERPs	ERPs	Pre-ERPs	ERPs
Soil erosion	Cropland	OLS	0.17	-0.02	61	125	0.53**	0.41**
		GWR	0.73	0.72	50	101	0.07	0.01
	Woodland	OLS	-0.03	0.03	67	123	0.55**	0.46**
		GWR	0.53	0.72	62	93	0.16*	0.09
	Grassland	OLS	0.17	-0.03	61	125	0.37**	0.42**
		GWR	0.63	0.81	54	96	-0.001	0.08
Water yield	Cropland	OLS	0.01	-0.01	185	70	0.67**	0.62**
		GWR	0.87	0.61	137	51	0.34**	0.06
	Woodland	OLS	0.06	0.07	184	67	0.61**	0.49**
		GWR	0.84	0.70	140	47	0.37**	0.14
	Grassland	OLS	-0.03	0.04	187	68	0.68**	0.55**
		GWR	0.89	0.71	137	43	0.26**	0.12

* Correlation is significant at the 0.01 level. ** Correlation is significant at the 0.05 level.

In order to more elaborately detect the spatial structure of residuals from OLS and GWR models, the local indicators of spatial association (LISA) for pre-ERPs period was calculated (Figure 6-1). The LISA is to evaluate the degree of local spatial autocorrelation at each sampling point using a local Moran's *I*. As shown in Figure 6-1, local Moran's *I* statistics on the residuals from GWR models within the spatial scale range are smaller than or equal to those from OLS models. Especially the results of LISA for the LULC in relation to soil erosion from GWR is better than the results from OLS. For example, Low-Low autocorrelation between LULC and soil erosion in GWR was observed only in one or two sub-watersheds, and in most sub-watersheds no spatial autocorrelation was observed. The results of the LISA analysis demonstrate that GWR has a better ability to model spatially varying data with very minimal clustering of residuals. Moreover, Table 6-2 shows the condition number in all GWR models. Results are unstable in the presence of multicollinearity as indicated by a condition number greater than 30. In this study, all the condition numbers from GWR with all explanatory variables are smaller than 30, which means that there is no strong multicollinearity, and the results are reliable. Thus, compared with corresponding OLS parameters, GWR models are characterized by higher adjusted R^2, lower AIC values, and less spatial auto-autocorrelation denoting their stronger ability to explain variances in the relationships between LULC and water-related ES.

Table 6- 2 Condition number in all GWR analysis

Pre-ERPs period				
	Condition number	Cropland	Grassland	Woodland
Soil erosion	Min.	1.0	1.0	1.0
	Max.	9.9	3.4	2.4
Water yield	Min.	1.0	1.0	1.0
	Max.	3.5	3.9	2.5
ERPs period				
	Condition number	Cropland	Grassland	Woodland
Soil erosion	Min.	1.0	1.1	1.7
	Max.	8.7	8.3	3.4
Water yield	Min.	1.0	1.0	1.4
	Max.	5.6	3.3	3.7

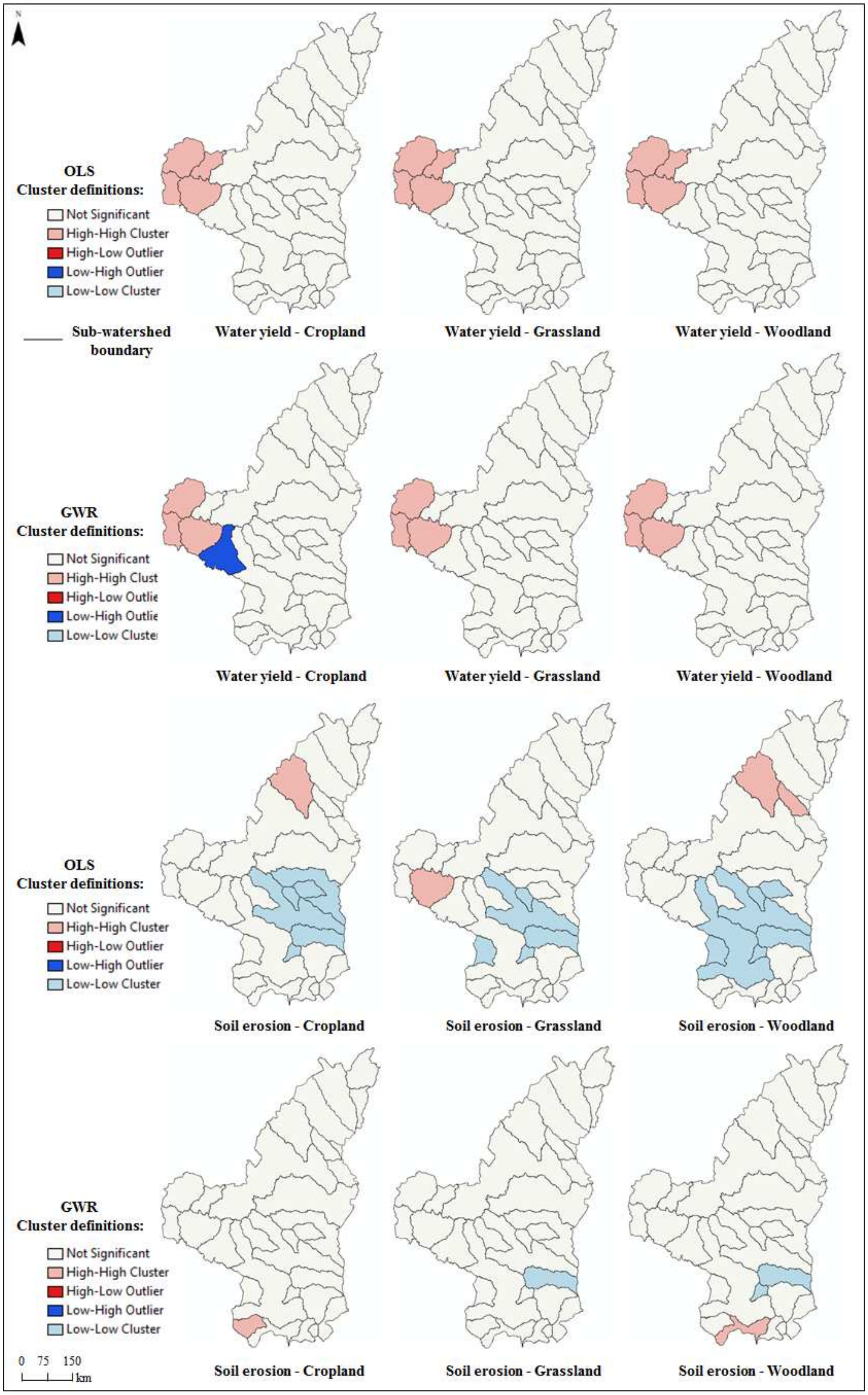

Figure 6- 1 Results of the local spatial autocorrelation of OLS and GWR model residuals for all variables

6.1.2 Impacts of LULC change on soil erosion

Spatial patterns of local R^2 for independent variables of the change rates of cropland, woodland, and grassland are shown in Figure 6-2. It was found that local R^2 values changed spatiotemporally for different LULC in both pre-ERPs and ERPs periods. As shown in Figure 6-2a, the best fit models are the change rate of cropland and grassland as the dependent variables, and the best fit model is located in the central regions and part of southern regions in the study site. These results indicated that local models are performing well in these regions. The lowest local R^2 value is the change rate of woodland as the dependent variable. Except sub-watershed No.9, local R^2 values in the rest of sub-watersheds showed less than 0.25, indicating that the local models in these sub-watersheds were performing not as good as in the sub-watershed No.9. As shown in Figure 6-2b, the best fit model in the ERPs period is the change rates of cropland and grassland as the dependent variables, with the highest local R^2 0.74. Spatial patterns of local R^2 varied from one sub-watershed to another. Lower local R^2 values (less than 0.3) for the change rates of cropland and woodland were observed at the northern and western regions, indicating that the local models in these sub-watersheds did not perform very well.

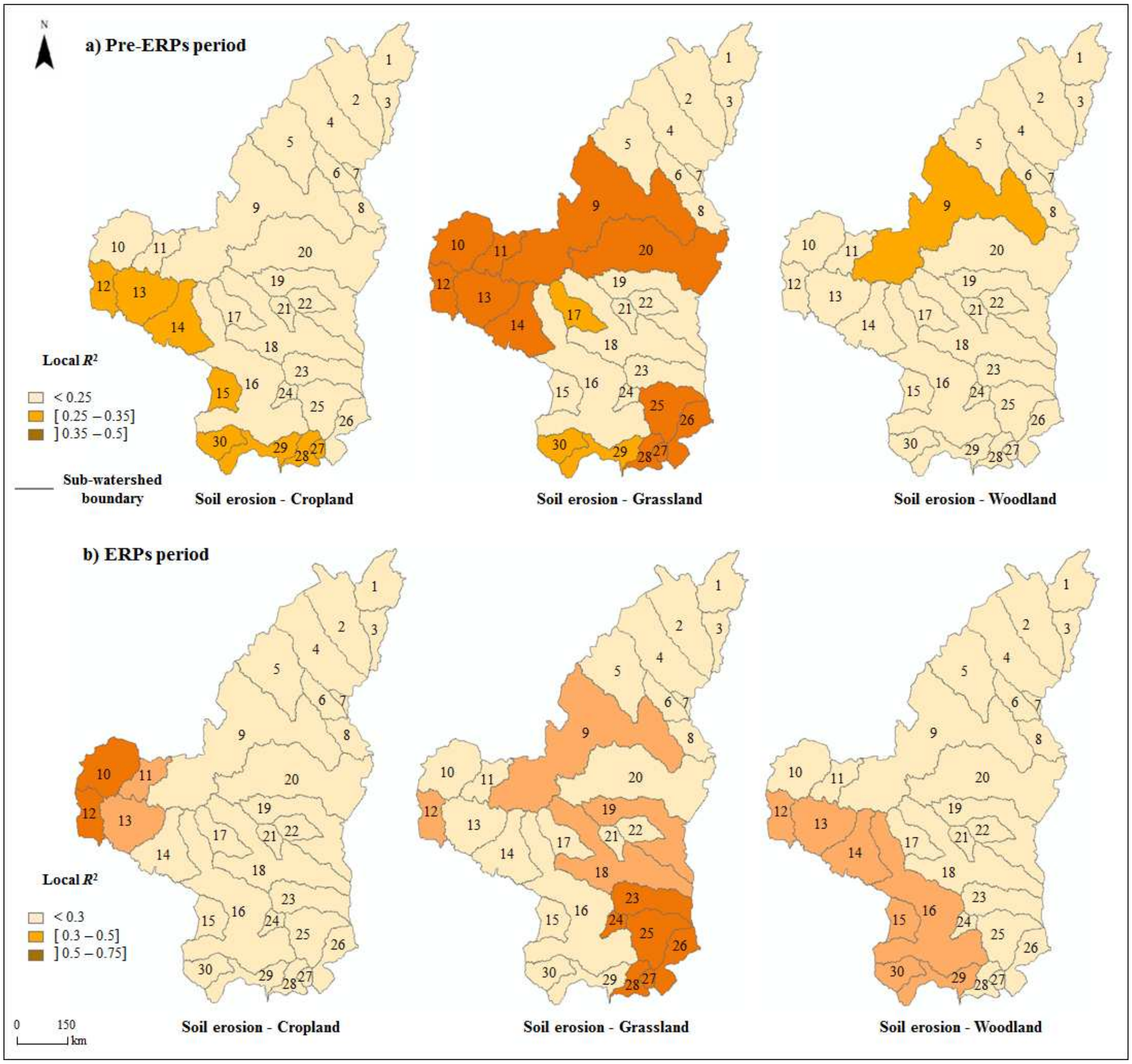

Figure 6- 2 Spatial patterns of local R^2 between the change rate of soil erosion and the change rates of LULC in pre-ERPs (a) and ERPs periods (b). Sub-watersheds are numbered from 1 to 30.

Figure 6-3 shows the local estimates for the regression coefficient of the change rate of cropland from 1988 to 2015, which is used to represent spatial varying relationships between croplands and soil erosion. The relationship between cropland and soil erosion is not constant over space in northern Shaanxi. As for the pre-ERPs period, a negative relationship between croplands and soil erosion change rates existed in the south and west sub-watersheds, indicating that cropland increase in these regions might not cause an increase soil erosion from 1988 to 2000. A positive relationship can be seen in the central and north sub-watersheds. During the pre-ERPs period, areas of cropland increased by 266 km^2, and soil erosion estimated from croplands decreased by 35 million tonnes. Soil erosion in the whole study site decreased by 0.12 billion tonnes. Our GWR analysis showed that areas of sub-watershed which represented a positive relationship accounted for 41% of total area, while 59% of total area represented a negative relationship in northern Shaanxi.

As for the ERP period, the negative relationship only existed in four sub-watersheds in northern Shaanxi. A positive relationship existed in the rest of sub-watersheds, indicating that higher cropland increase is linked to higher soil erosion increase. During the ERPs period, areas of cropland decreased by 3696 km^2, and soil erosion estimated from croplands decreased by 163 million tonnes. Soil erosion in the whole study site decreased by 0.32 billion tonnes. At the same time, areas of sub-watershed which represented a positive relationship accounted for 95% of total area, while 5% of area showed a negative relationship in the study site. Our relationship analysis results indicate that increasing cropland area can increase the risk of soil erosion in most sub-watersheds in northern Shaanxi. In other words, the ERPs can help reduce the risk of soil erosion in this region.

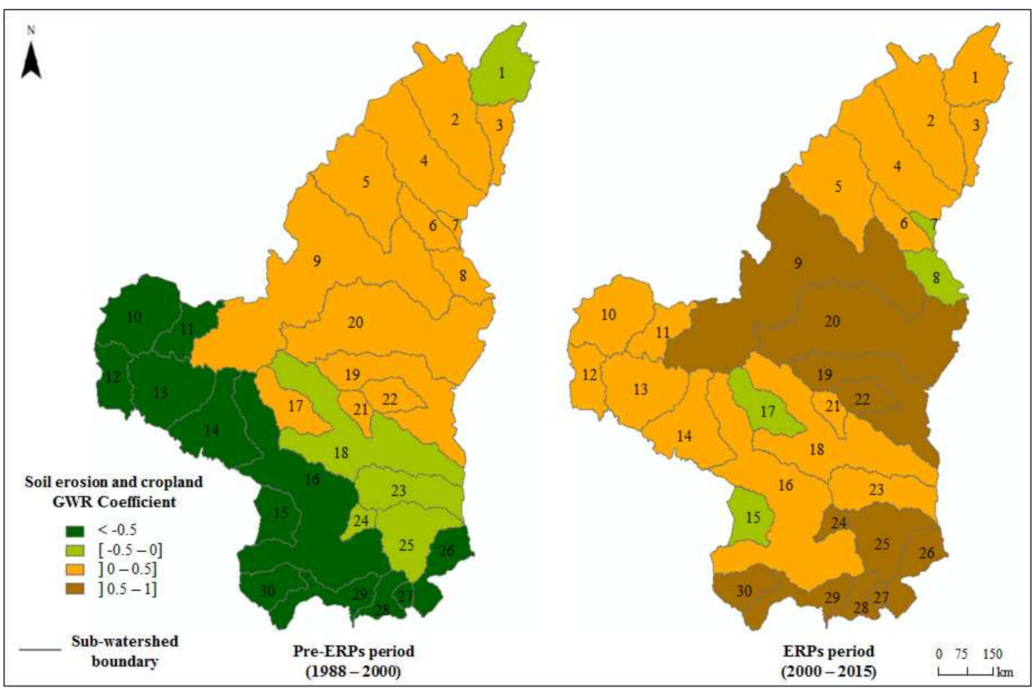

Figure 6- 3 The relationship between the change rate of cropland and the change rate of soil erosion in northern Shaanxi from 1988 to 2015. Sub-watersheds are numbered from 1 to 30.

Figure 6-4 shows the local estimates for the regression coefficient of the change rate of woodland from 1988 to 2015. As for pre-ERPs period, the relationships between woodland and soil erosion are not constant over space in northern Shaanxi. The negative relationship existed in most north and west sub-watersheds in northern Shaanxi, while the positive relationship existed in most south sub-watersheds. As for the ERPs period, the change rate of woodland has negative relationships with the change rate of soil erosion in sub-watersheds No. 1 to 9. However, a positive relationship exists in the rest of sub-watersheds. Areas of woodland increased by 174 km^2 during the pre-ERPs period, while areas of woodland increased by 1245 km^2 during the ERPs period. However, areas of sub-watersheds which represented a negative relationship between woodland and soil erosion decreased from 53% in the pre-ERPs period to 37% in the ERPs period. Our relationship analysis results indicate that increasing woodland area in these sub-watersheds might not always decrease the risk of soil erosion.

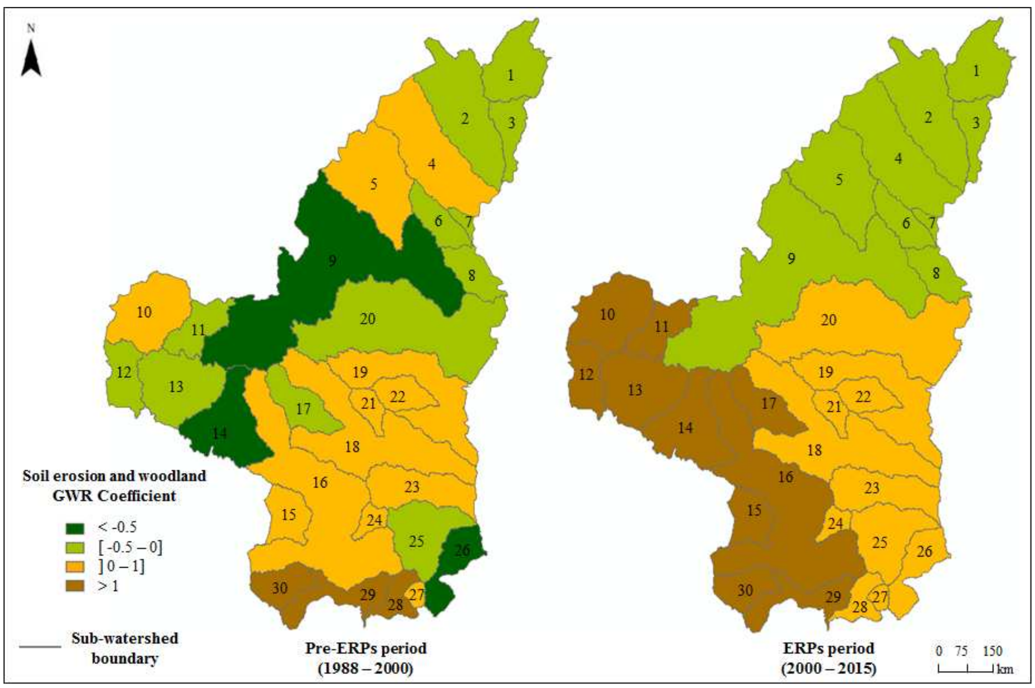

Figure 6- 4 The relationship between the change rate of woodland and the change rate of soil erosion in northern Shaanxi from 1988 to 2015. Sub-watersheds are numbered from 1 to 30.

Figure 6-5 shows the local estimates for the regression coefficient of the change rate of grassland from 1988 to 2015. This result indicates the relationship between grassland and soil erosion is not constant over space in northern Shaanxi. As for the pre-ERPs period, the change rate of grassland had negative relationships with the change rate of soil erosion in sub-watersheds No. 1 to 4. The result suggests that increase of grassland can help reduce soil erosion. However, other sub-watersheds represented a positive relationship between grasslands and soil erosion. As for the ERPs period, the negative relationship between grasslands and soil erosion expanded to eleven sub-watersheds, indicating that the positive impacts of grassland on soil erosion in the study site. Areas of grassland increased by 783 km^2 from 1988 to 2000, while the grasslands in northern Shaanxi increased by 1494 km^2 from 2000 to 2015. Areas of sub-watersheds which represented a negative relationship between woodland and soil erosion increased from14% in the pre-ERPs period to 47% in the ERPs period. In contrast, 53% of the area is showing a positive relationship during the ERPs period, indicating that increasing grassland area might not always decrease soil erosion in northern Shaanxi.

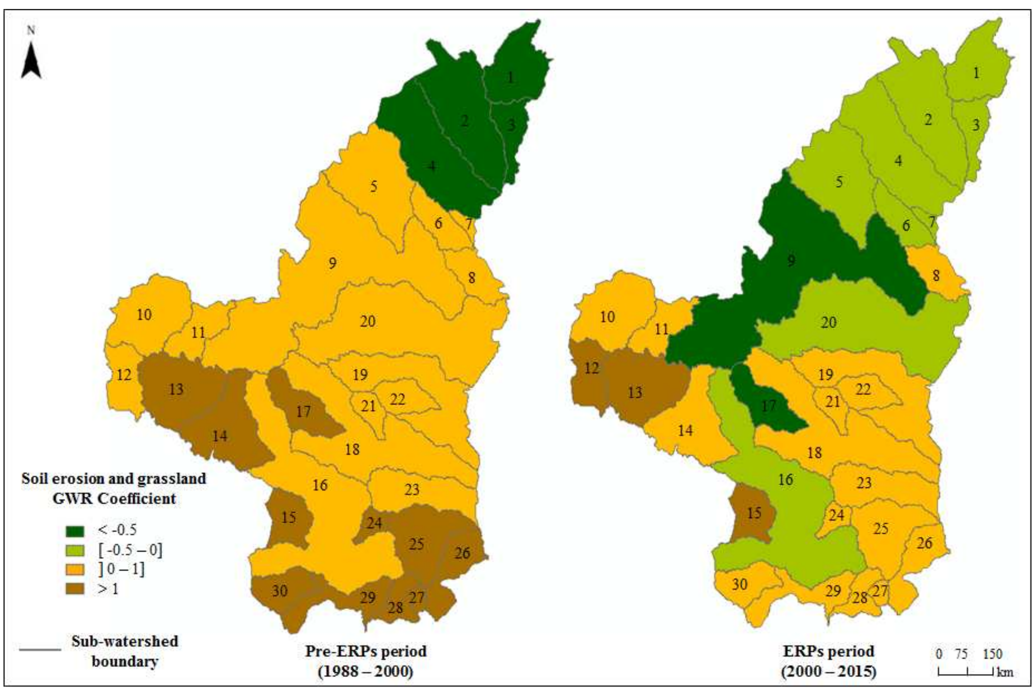

Figure 6- 5 The relationship between the change rate of grassland and the change rate of soil erosion in northern Shaanxi from 1988 to 2015. Sub-watersheds are numbered from 1 to 30.

6.1.3 Impacts of LULC change on water yield

Spatial patterns of local R^2 for independent variables of the change rates of cropland, woodland, and grassland are shown in Figure 6-6. The local R^2 values changed spatiotemporally for different LULC types in both pre-ERPs and ERPs periods. As shown in Figure 6-6a, local models did not perform well in most sub-watersheds in the pre-ERPs period, because the values of local R^2 in many sub-watersheds are less than 0.3. Local R^2 of the ERPs period are better than the pre-ERPs period, indicating that local models performed better for this period. Moreover, higher local R^2 is found in northern regions and part of southern regions in the study site, indicating that local models performed well in these regions. The best fit model is the woodland as the dependent variable, and local R^2 values range from 0.18 to 0.84 in the ERPs period.

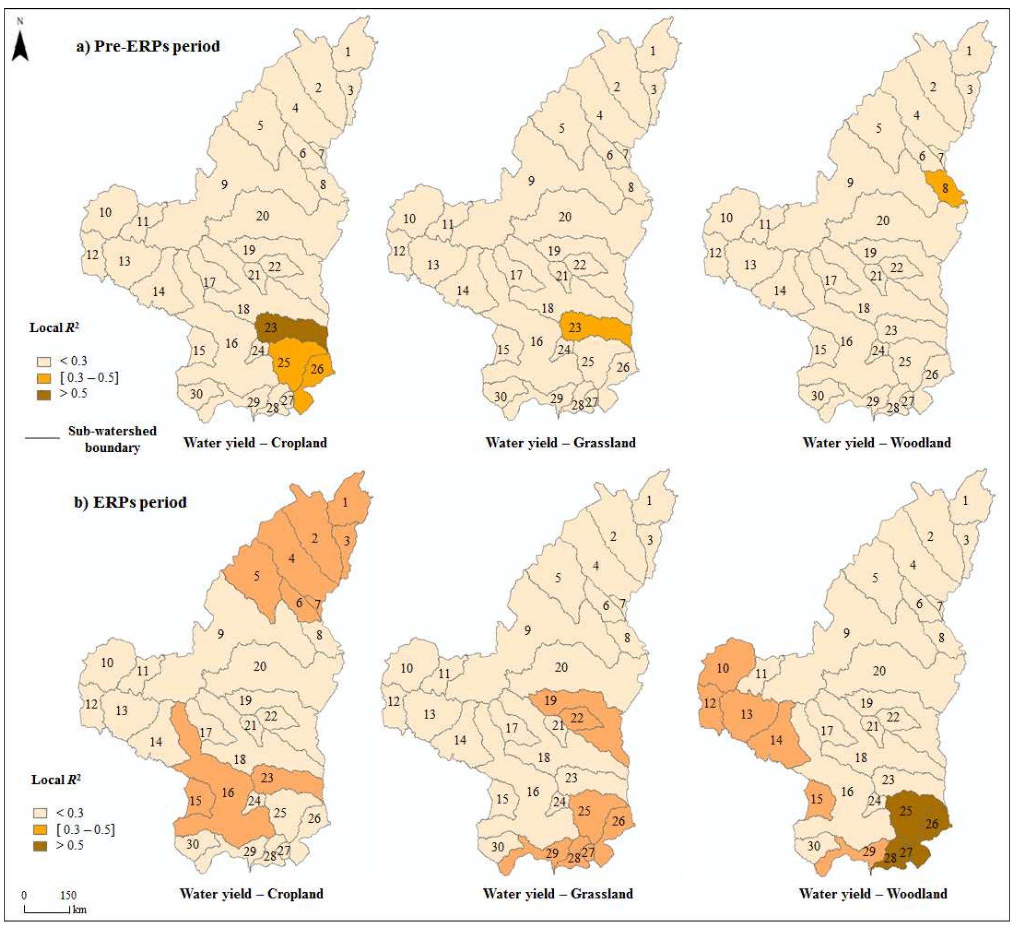

Figure 6- 6 Spatial patterns of local R^2 between the change rate of water yield and the change rates of LULC in pre ERPs (a) and ERPs periods (b). Sub-watersheds are numbered from 1 to 30.

Figure 6-7 shows the local estimates for the regression coefficient of the change rate of cropland from 1988 to 2015, which is used to represent spatial varying relationships between cropland and water yield. As for the pre-ERPs period, the change rate of cropland had positive relationships with the change rate of water yield in the north regions. The rest regions in northern Shaanxi showed negative relationship between croplands and water yield, but to different degrees. The coefficients in the sub-watersheds No. 11 to 13, were less than -2, while the coefficients in the sub-watersheds No. 14 to 30 ranged from -2 to 0. The negative relationship existed in west and south sub-watersheds. As for the ERPs period, the positive relationship between croplands and water yield expanded to twenty-six sub-watersheds, while the negative relationship between croplands and water yield existed only in four sub-watersheds.

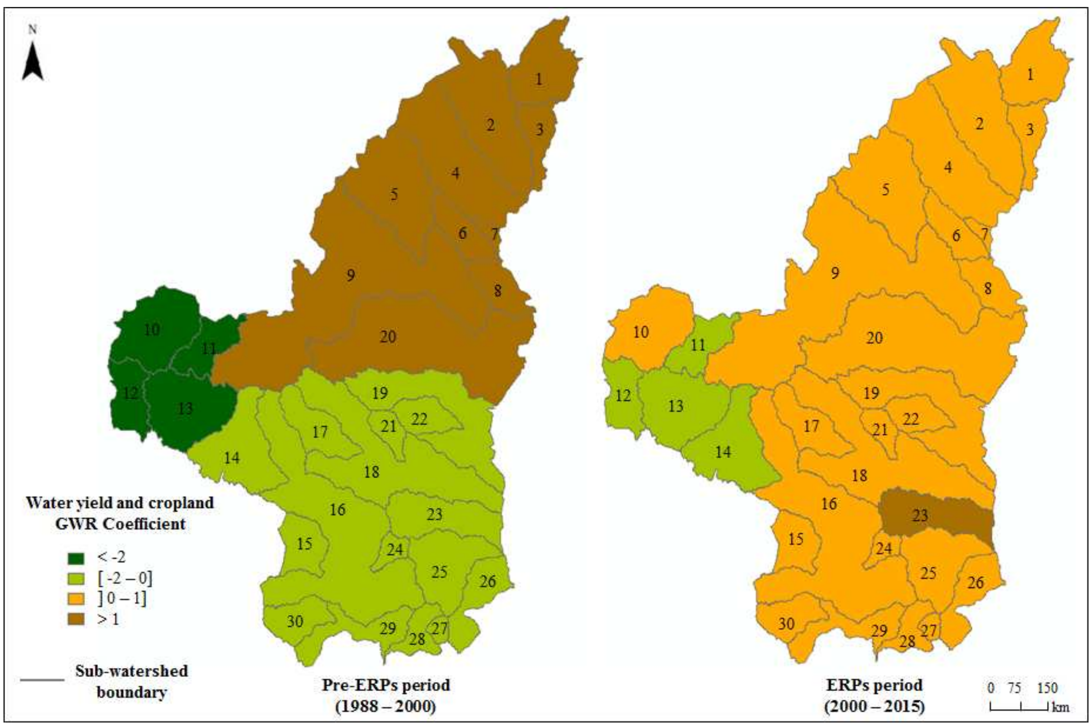

Figure 6- 7 The relationship between the change rate of cropland and the change rate of water yield in northern Shaanxi from 1988 to 2015. Sub-watersheds are numbered from 1 to 30.

Figure 6-8 shows the local estimates for the regression coefficient of the change rate of woodland from 1988 to 2015. During the pre-ERPs period, a negative relationship existed in the north sub-watersheds, while the positive relationship existed in most south sub-watersheds. As shown in Figure 6-8, the change rate of woodland has negative relationships with the change rate of water yield in twenty-one sub-watersheds, while a positive relationship exists in the rest of sub-watersheds during the ERPs period. Areas of woodland increased by 174 km^2 during the pre-ERPs period, while it increased by 1245 km^2 during the ERPs period. However, the area of sub-watersheds which represented a negative relationship between woodland and water yield increased from 50% in the pre-ERPs period to 65% in the ERPs period. This result indicated that the EPRs show a negative impact on water yield in northern Shaanxi.

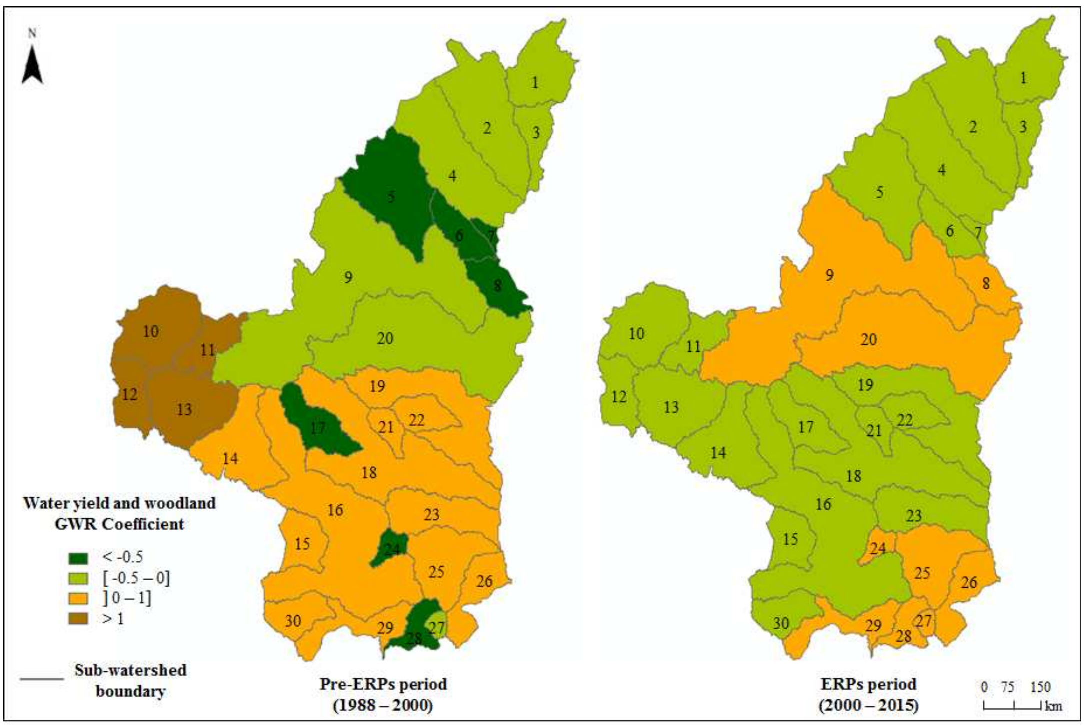

Figure 6- 8 The relationship between the change rate of woodland and the change rate of water yield in northern Shaanxi from 1988 to 2015. Sub-watersheds are numbered from 1 to 30.

Figure 6-9 shows the local estimates for the regression coefficient of the change rate of grassland from 1988 to 2015. Spatial heterogeneity existed in the relationship between grasslands and water yield in the pre-ERPs and ERPs periods. As for the pre-ERPs period, the change rate of grassland had negative relationships with the change rate of water yield in sub-watersheds No. 1 to 11, 19 and 22. However, other sub-watersheds represented a positive relationship between grasslands and water yield. After implementation of the ERPSs, a negative relationship between grasslands and water yield represented in sub-watersheds No.1 to 9, 15, and 17, while the other sub-watersheds had a positive relationship. Areas of grassland increased by 783 km^2 from 1988 to 2000, while it increased by 1494 km^2 from 2000 to 2015. Areas of sub-watersheds which represented a negative relationship between grassland and water decreased from 48% in the pre-ERPs period to 40% in the ERPs period. Our relationship analysis results indicated that increasing grassland area might not always decrease water yield in northern Shaanxi.

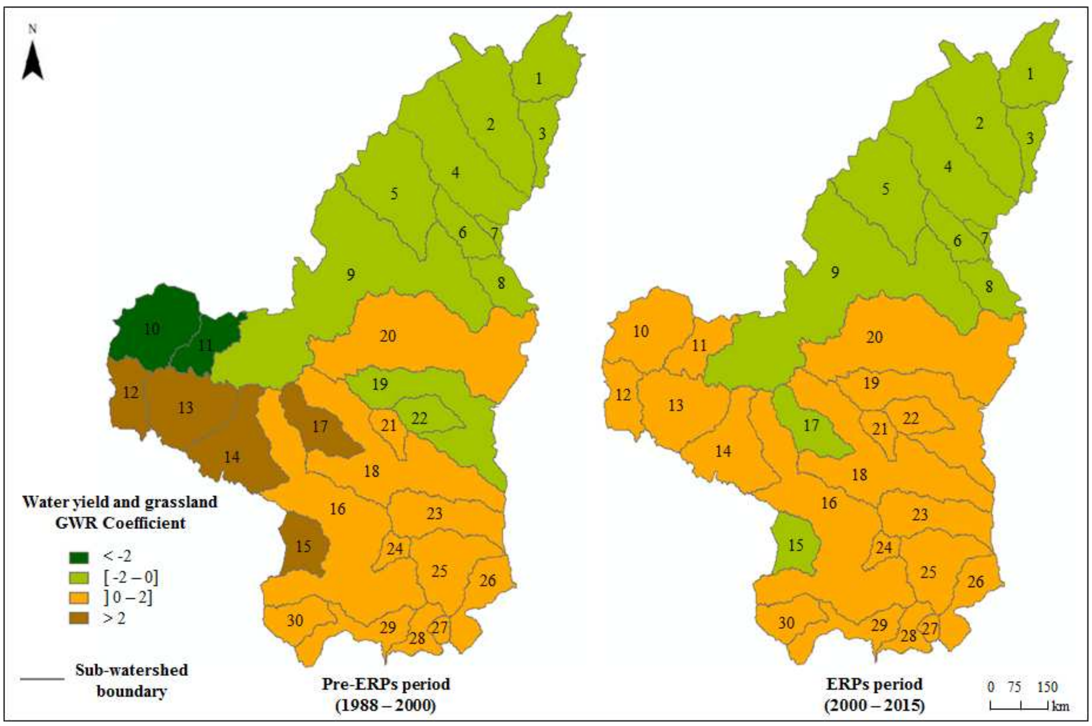

Figure 6- 9 The relationship between the change rate of grassland and the change rate of water yield in northern Shaanxi from 1988 to 2015. Sub-watersheds are numbered from 1 to 30.

6.2 The relationships between soil erosion and water yield

As shown in Figure 6-10, soil erosion was found to have significant correlations with water yield at different years. In this study, it was found that water yield is positively correlated with soil erosion during the entire monitoring period in Pearson correlation analysis, suggesting that when the amount of water yield increases, the risk of soil erosion is likely to increase and vice versa. It is seen that the high coefficient indicates a strong positive relationship between soil erosion and water yield in 1988 and 2000. However, the relationships between water yield and soil erosion were weakened after implementation of the ERPs in northern Shaanxi.

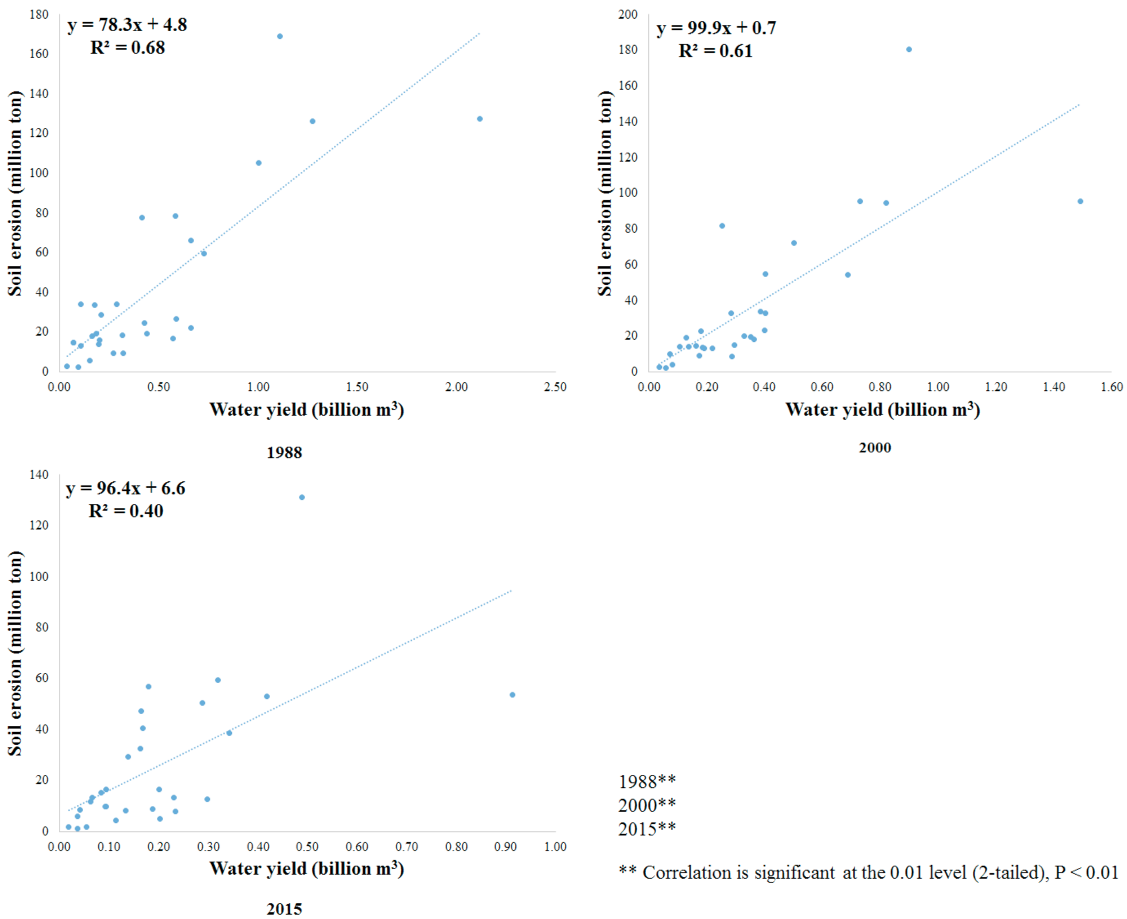

Figure 6- 10 The correlations between soil erosion and water yield in three different years

6.3 Discussion

6.3.1 Spatial heterogeneity of relationships between LULC and water-related ES during ERPs period

6.3.1.1 Spatial heterogeneity of relationships between soil erosion and LULC during ERPs period

In terms of relationships between soil erosion and LULC, it was found that 95% of the study area showed a positive relationship, indicating that higher cropland increase is linked to higher soil erosion increase. Our soil erosion quantification result indicated that soil erosion mainly came from croplands. In other words, decreasing of cropland can help reduce the risk of soil erosion. Moreover, it was found that spatial heterogeneity of relationships between LULC and soil erosion existed in northern Shaanxi, indicating that the ERPs implemented in northern Shaanxi might not always help reduce soil erosion. Vegetation cover controls erosion by reducing erosive forces, including providing protection of the soil surface against raindrop impact and against erosion by surface runoff, reducing runoff volume and velocity by increasing infiltration rate and surface roughness, and reducing sediment transport by trapping sediments (Gumiere et al., 2011; Vannoppen et al., 2015). However, vegetation types and their growth status, structure and distribution have great impacts on controlling runoff and erosion (Hartanto et al., 2003; Tian et al., 2003; Huang et al., 2010). Some researchers have found that effects of vegetation on reducing soil erosion were almost equivalent (Pan et al., 2006; Wei et al., 2007). In northern Shaanxi, grasslands have different canopy cover, which lead to different capacity to resist soil erosion (Figure 6-11). Grasslands are divided into three types: sparse (grasslands with canopy cover between 5% and 20%), moderate (grasslands with canopy coverage between 20% and 50%), and dense (grasslands with canopy coverage greater than 50%). Thus, even grasslands accounted for higher percentage of total area in some sub-watersheds, these grassland growth stage can limit their capacity to resist soil erosion. Moreover, it was found that the estimates of total soil erosion mainly came from croplands, moderate grasslands, and sparse grasslands. Chen et al. (2018) pointed out that the grassland with the high ground cover are more effective in controlling surface soil erosion, while forestlands with poor ground cover generate more surface runoff and associated soil erosion. In other words, the capacity of forest to resist soil erosion depends on the ground cover.

Moreover, soil erosion can be linked not only to vegetation but also to topography, climate, and soil properties (Ekwue and Harrilal 2010). Firstly, soil texture has a great effect on erosion due to differing infiltration rates and variations in the ease or difficulty of particle detachment (Xu et al., 2013). Generally, compact clay-based soils are less prone to erosion in comparison to loosely-bound sandy soils. Higher percentage of sand is distributed in north sub-watersheds. Moreover, these regions usually had higher percentage of croplands and lower percentage of woodlands. For example, the cropland area was 59% in 1988 and 53% in 2015, while the woodland area was only 2% in 1988 and 4% in 2015 in sub-watershed No.8. Thus, soil erosion might be sensitive on afforestation or converted cropland to forests and grasslands in these sandy soil and lower vegetation cover regions.

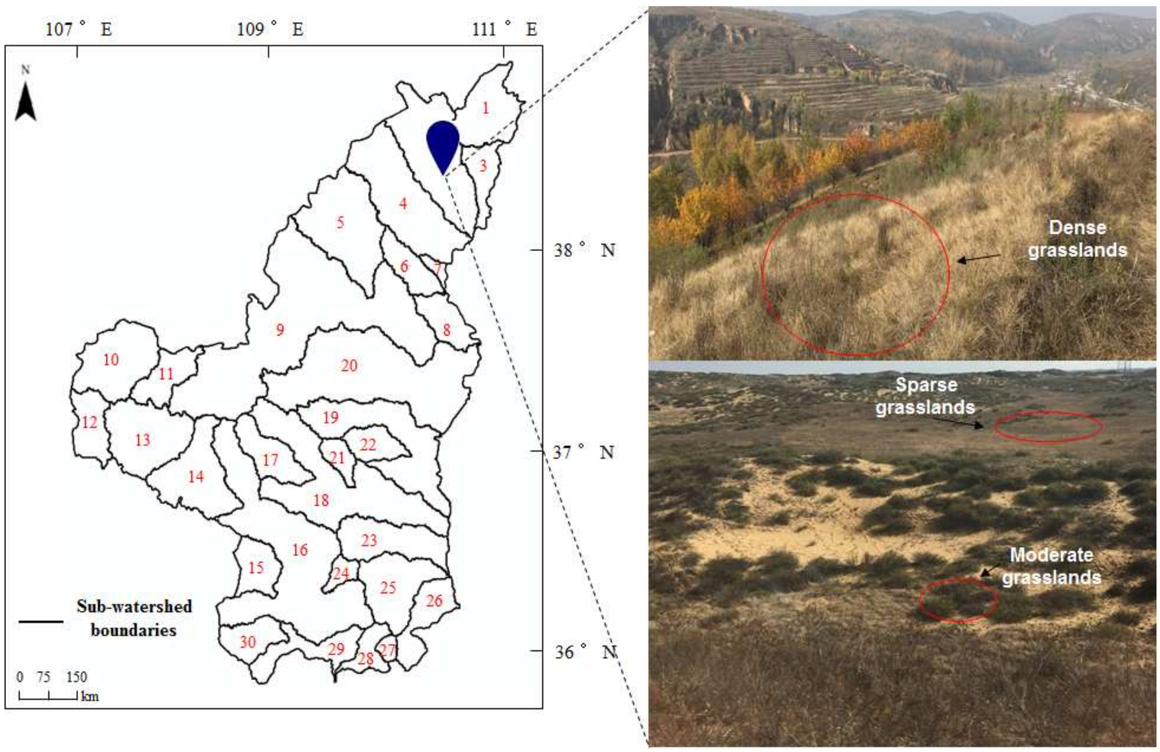

Figure 6- 11 Example of sparse, moderate, and dense grassland in the study site, photos by Xin Wen. Sub-watersheds are numbered from 1 to 30.

Secondly, a slope with a steep angle can have a greater impact on the soil composition compared to a gentle slant. As rain falls, soil can move down the steep slope, especially if vegetation is scarce or water amounts become excessive. It was found that slopes more than 25 degrees are distributed in most northern sub-watersheds (e.g. sub-watersheds No. 5 to 7). Farming on sloping lands is another important driving force behind soil erosion (Zhang et al., 2004). Most of the soil loss happened on steep slopes regions in the Loess Plateau (Wang et al., 2017). Thus, afforestation or converted cropland to forests and grasslands in north sub-watersheds might be sensitive on soil erosion in comparison to southern sub-watersheds which are usually covered by higher woodlands with clay-based soil or silt-based soil.

Lastly, rainfall events are important in affecting erosion processes, because the impacts of raindrop on soil surface in high-intensity storms can cause increased soil particle detachment and greater transport of suspended sediment load (Van Dijk et al., 2002). Northern Shaanxi is located in the arid and semi-arid regions which are usually characterized by excessive heat and low precipitation. Rainfall in this region decreases from the south to the north. In particular, according to weather station records in 1988, 2000, and 2015, the days of rainfall events more than 12 mm in north sub-watersheds was less than south sub-watersheds. For example, the days of rainfall more than 12 mm in weather station No.53646 which is located in north region was 11 days in 2015, while it was 16 days in weather station No. 53942 which is located in south sub-watersheds in 2015. Thus, the sub-watersheds located in the south regions might be at higher risk of rainfall erovisity compared to the sub-watersheds located in the north regions. In other words, compared with the north sub-watersheds, the ERPs implemented in southern sub-watersheds might not always help reduce the risk of soil erosion.

6.3.1.2 Spatial heterogeneity of relationships between water yield and LULC during ERPs period

LULC have potentially large impacts on water resources, because changes in LULC can result in some proportional alterations in the watershed condition and hydrological response (Stonestrom et al., 2009). Several studies have concluded that water yield can be reduced by reforestation practices (Trabucco et al., 2008; Ellison et al., 2017). Our results firstly indicated that the amount of water yield in all sub-watersheds decreased during the ERPs period, implying that increasing woodlands and grasslands might decrease the amount of water yield to some degree. However, it was found that the relationships between LULC and water yield are not constant over space in northern Shaanxi, indicating that LULC changes might not be the single driving force which can cause water yield decline in northern Shaanxi. After implementation of the ERPs, a negative relationship between woodlands and water yield existed in twenty-one sub-watersheds, accounting for 65% of the total area, and a negative relationship between grasslands and water yield was shown in eleven sub-watersheds, accounting for 40% of the total area.

Forests are intimately linked to precipitation and water availability, because they played an important role in regulating fluxes of atmospheric moisture and precipitation patterns over land (Ellison et al., 2017). Earth's land and ocean surfaces release water vapor to the atmosphere. This process is aided by forests and other vegetation through ET_0 on continental surfaces. Earlier studies have suggested that increases in leaf area and tree cover have led to a decline in soil moisture and runoff due to increased ET_0 (Trabucco et al., 2008), especially in dry regions of China (Li et al., 2017). In this study, it was found that average annual ET_0 and precipitation from 1988 to 2013 showed a slight increase tendency in northern Shaanxi. However, the amount of water yield did not increase from 1988 to 2013 in northern Shaanxi. After implementation of the ERPs, woodlands and grasslands rapidly increased in comparison to the pre-ERPs period. Woodlands and grasslands must consume water in order to ensure their own survival. Plants with high stem volumes allow transpiration to outstrip root uptake, as stem water reserves are depleted by day and replenished at night (Sheil and Murdiyarso 2009). Forests typically have deeper roots than other vegetation and can thus access subterranean moisture during droughts (Wen et al., 2010).

The hydrological cycle can be directly or indirectly affected by changes in climate and human activities (Sala et al., 1997; Hao et al, 2017). Especially it is more vulnerable to anthropogenic disturbance and natural change in semi-arid and arid regions (Liu et al., 2004; Zhang et al., 2008). Climate variables usually include precipitation, temperature, and radiation. In this study, the InVEST annual water yield is employed to calculate the amount of water yield at watershed scales, and this model is based on the Budyko theory, which has a long history and continues to receive interest in the hydrological literature (Zhang et al., 2004; Donohue et al., 2012). The Budyko curve is a unique empirical function that relates the ratio of actual to potential evapotranspiration to the ratio of precipitation to potential evapotranspiration (Budyko, 1974). The character of precipitation in this region decreases from the south to the north. Spatial heterogeneity of precipitation might be an important factor which can affect the amount of water provision.

However, due to the lack of long-term consecutive temporal precipitation, woodland attributes (i.e. tree species, stand age and structure), and soil moisture data, it is hard to directly analyse the relationship between precipitation, ET_0 and water yield in detail in this study. Several recent studies have analysed the complexity of human activities in shaping runoff in the Loess Plateau under a changing climate for a long-term period. Feng et al.

(2017) identified the roles of human activities (e.g. the ERPs) in runoff trends and their interaction with climate factors (e.g. precipitation) in the Loess plateau from 1961 to 2009. Their results indicated that reduced precipitation was the dominant factor causing reduction in runoff over the entire study period, while the ES of water provision decreased after human intervention, such as implementation of the ERPs. Moreover, a statistically significant climatic drying starting from 2000 (Zhang et al., 2015). Zhang et al. (2016) suggested that the water yield decrease in the Loess Plateau in the 2000s could be attributed to both climate aridity and afforestation in this region.

6.3.2 Trade-offs and synergies in ecosystem services

In a semi-arid and arid region, the relationship between soil erosion and water yield under LULC changes was analysed. It was found that trade-offs existed in soil erosion and water yield, which means an improvement in erosion service is achieved at the expense of a decrease in provision water in northern Shaanxi. Soil erosion and water yield are correlated possibly because they share the common hydrological conditions (e.g. precipitation) and the common driver of LULC changes. Soil erosion is affected by rainfall, topography and vegetal cover factors. Among these factors, rainfall intensity is a very important factor (Ran et al., 2012). In this study, daily rainfall more than 12 mm is used as the standard for calculating erosive rainfall. Xie et al. (2000) found that 12 mm could be the standard for describing erosive rainfall on the Loess Plateau, and this criterion has been widely accepted (Zhang 2003; Cheng et al. 2009). The close relationship between soil erosion and rainfall intensity is because the impacts of raindrop on soil surface in high-intensity storms can cause increased soil particle detachment (Van Dijk et al., 2002).

This result has already been supported by other modeling ES studies in recent years. Yu et al. (2018) pointed out that land use planning operations reduced the maximum runoff and total water yield as well as the total sediment loads in Huaihe River basin, China. Cao et al. (2010) pointed out that massive planting trees without considering the local environmental conditions might not obtain the expected ecological goals, and even causing potential environmental problems. As discussed above, both positive and negative impacts of the ERPs on ES are possible. This result suggests that the current ERPs in the semi-arid regions may need to be modified. If the meteorological conditions remain stable in the future, increasing the area of woodland as a result of the current ERPs may potentially decrease annual water yield in this region. Therefore, Chapter 7 is to analyse what levels of the ERPs should be maintained in northern Shaanxi through designing different LULC change scenarios.

The trade-offs and synergies among ES strongly depend on the basic structure and environmental conditions driven by biophysical and socio-economic factors (Hein et al., 2006). These driving factors usually have scale-dependent impacts on ecological processes due to their different functional ranges, and they usually are considered as the major factors that affect the spatial heterogeneity of ES (Tzanopoulos et al., 2013). Moreover, the sensitivity of ES relationships depends on the accuracy of ES quantifications. The relationships among ES may vary with changes in the temporal extent. Thus, quantifying and mapping the value of ES and modelling the dynamic trends in ES relationships should be considered. Although spatial variations in ES may be caused by similar factors, these ES are not necessarily driven by the same processes. Thus, extra biophysical and socio-economic driving forces must be explored to clarify ES relationships.

6.3.3 Uncertainties of GWR model to explore the spatial relationships

The high spatial variability of LULC and water-related ES (Chapter 5) suggest that significant spatial non-stationarity might exist in the relationships between LULC types and water-related ES over the study area. Spatial non-stationarity means that the relationships between independent and dependent variables are not constant over space (Fotheringham et al., 2002). Thus, GWR is a more appropriate method than traditional regression techniques in northern Shaanxi. In this study, GWR models reveals the detailed site information on the relationships between different LULC and water-related ES in the study area, which improves the model ability to explain the local situation of the impacts of the ERPs on water-related ES and is helpful for developing more effective plans and policies to maximize the positive benefits of the ERPs on ES.

Ecosystem functions and processes are usually location-dependent and auto-correlated, because many ecosystem functions and processes exhibit highly spatial heterogeneity and autocorrelation (Raudsepp-Hearne and Peterson, 2016), which make it difficult to meet the assumptions and requirements of the OLS model. In this study, significant positive spatial autocorrelations are found for all the OLS models and all the GWR models in pre-ERPs period, which might affect the GWR model accuracy. Moreover, LeSage (2004) summarized major disadvantages of GWR modeling. Firstly, the lack of independence among local estimates may lead to the failure in valid inferences for the local estimates. Secondly, inappropriate local coefficients may be caused by the presence of outliers. Thirdly, when the number of sample is quite small, the estimated local coefficients may be ineffective or invalid. Pixel-based GWR analysis was considered in this study. In the pixel-based GWR analysis, sampling blocks (10 × 10 km and 5 × 5 km) were intersected with the LULC, soil erosion and pixel-based water depth maps into each block. Compared with watershed-based GWR analysis, the main advantages of pixel-based GWR analysis are relatively substantial sample numbers. For soil erosion, the pixel-based GWR analysis can be used. However, final results of water yield have to be represented at the sub-watershed scale. In hydrology, the land unit is the watershed, which also may be referred to as a basin or catchment (Edwards et al., 2015). It is more rational analyzing water yield based on watershed scales. Thus, it is difficult to make a comparison between pixel-based soil erosion GWR and watershed-based water yield GWR.

6.3.4 Correlation analysis in ES trade-off and synergy analysis

Recent studies focusing on multiple ES have taken several perspectives. The concept of bundles of ES has been commonly applied in ES assessments in a landscape, which tries to identify multiple ES derived from the different LULC types (Haines-Young et al., 2012; Mouchet et al., 2014; Lee and Lautenbach 2015). It is frequently based on a GIS analysis (e.g. mapping ES values) at the landscape or the regional scale (e.g. Xu et al., 2017). GIS-based spatial mapping combined with correlation analysis on the interactions among ES is a useful tool to provide specific information for trade-off or synergy analysis (Deng et al., 2016). Statistical techniques (e.g. correlation analysis and OLS analysis) is a powerful tool to identify ES bundle types and analyse ES trade-offs and synergies (e.g. Su and Fu 2013; Wang et al., 2014).

The simplicity of the correlation as presented in this study makes it an ideal starting point for assessing the trade-offs and synergies between soil erosion and water yield. However, understanding the trade-off and synergy among multiple ES requires considering multiple spatial scales (Liu et al., 2017). Ecological functions and processes change at different scales, which is known as the scale effect (Hurlbert and Jetz 2007). This feature is particularly apparent for spatial scales, which are represented by spatial heterogeneity as well as hierarchical variability. Ecosystems have different horizontal and hierarchical structures that determine ES spatial-scale features and further influence ES relationships (De Groot et al., 2010). Correlation analysis used in this study might not interpret the relationships at multiple spatial scales. The GWR was considered to analyse the relationship between soil erosion and water yield at sub-watershed scale. However, the results of Moran's *I* on the residuals from GWR models showed auto-correlation in both pre-ERPs and ERPs periods, suggesting that the GWR outputs might not be robust in this study.

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Chapter 7 Scenario analysis

Summary

In this Chapter, the potential impacts of ERPs on water-related ES under different scenarios are analysed, and the level of the ERPs to be maintained in northern Shaanxi is discussed. Our major findings are listed as follows:

1. If continued, the ERPs are likely to have significant influent on soil erosion and water yield by 2050.
2. Compared with the baseline year (2015), soil erosion decreased under protection and business as usual (BAU) scenarios, but simulation results showed relatively small differences between both scenarios.
3. Water yield under BAU and No LULC change scenarios showed relatively small differences, indicating that climate factors (e.g. precipitation and ET_0), ecological restoration and their interactions are likely to place substantial pressures on the provision of water by 2050.
4. Current ecological restoration practices might support soil and water conservation in the future in northern Shaanxi.

Résumé

Dans ce chapitre, les impacts potentiels des PRE sur les SE liés à l'eau dans différents scénarios ont été analysés et le niveau de PRE à maintenir dans le nord du Shaanxi est discuté. Nos principaux résultats sont énumérés comme suit :

1) S'ils se poursuivent, les PRE auront probablement une influence significative sur l'érosion des sols et l'apport en eau d'ici 2050.
2) Par rapport à l'année de référence (2015), l'érosion des sols a diminué dans les scénarios de protection et de statu quo, mais les résultats de la simulation ont montré des différences relativement faibles entre les deux scénarios.
3) L'apport en eau dans les scénarios de statu quo et d'absence de changement d'occupation du sol a montré des différences relativement faibles, indiquant que les facteurs climatiques (précipitations et ET_0), la restauration écologique et leurs

interactions sont susceptibles d'exercer des pressions importantes sur l'approvisionnement en eau d'ici 2050.

4) Les pratiques actuelles de restauration écologique pourraient favoriser la conservation des sols et de l'eau dans le nord du Shaanxi.

7.1 Land use and land cover change scenarios

7.1.1 LULC scenario modeling assessments

The calibration results are assessed to measure the goodness of fit between the satellite-derived and the simulated LULC maps. Simulated LULC map for 2015 is compared with the satellite-derived map for 2015. The overall agreement for simulated 2015 LULC map is 87.37%, which reveals the consistency between the simulated result and actual LULC situation. Apart from overall classification accuracy, the confusion matrix give a more detailed description of the individual LULC class between simulated and satellite-derived maps (Table 7-1). As shown in Table 7-1, user's accuracy ranges from 78.73% to 100%. User's accuracy reflects the reliability of the classification to the user, which is the more relevant measure of the classification's actual utility in the field (Rwanga and Ndambuki 2017). Bare land is found to be more reliable with 78.73% of user accuracy, which is the lowest user's accuracy among six LULC classes. Moreover, producer's accuracy ranges from 34.79% to 96.62%. It reflects the accuracy of prediction of the particular category. The classess of woodland, bare land, cropland and water body in the simulated map for 2015 show a good fitness with the satellite-derived map for 2015. For example, 95.02% of croplands (18527 pixels) are classified correctly, and only 4.97% of croplands (969 pixels) are classified into grasslands. However, the classess of grassland and built-up land in the simulated map for 2015 show a less good fitness with the satellite-derived map for 2015. 78.42% of grasslands (11676 pixels) are classified correctly. Especially only 34.79% of built-up lands (1763 pixels) are classified correctly. 23.86 % of built-up lands (1209 pixel) are classified into bare lands, such as an example showing in Figure 7-1.

Table 7- 1 Confusion matrix of satellite-derived and simulated LULC map 2015

	Satellite-derived LULC (unit: pixel)							User's accuracy
Simulated LULC	C	W	G	W	BU	B	Total	(%)
C	18527	492	2829	164	958	0	22970	80.66
W	2	18966	0	0	50	134	19152	99.03
G	969	172	11676	0	1087	138	14042	83.15
W	0	0	0	2954	0	0	2954	100
BU	0	0	0	0	1763	0	1763	100
B	0	0	385	110	1209	6309	8013	78.73
Total	19498	19630	14890	3228	5067	6581	68894	
Producer's accuracy (%)	95.02	96.62	78.42	91.51	34.79	95.87		

Note: C= cropland; W=woodland; G=grassland; W=water body; BU= built-up land; B=bare land.

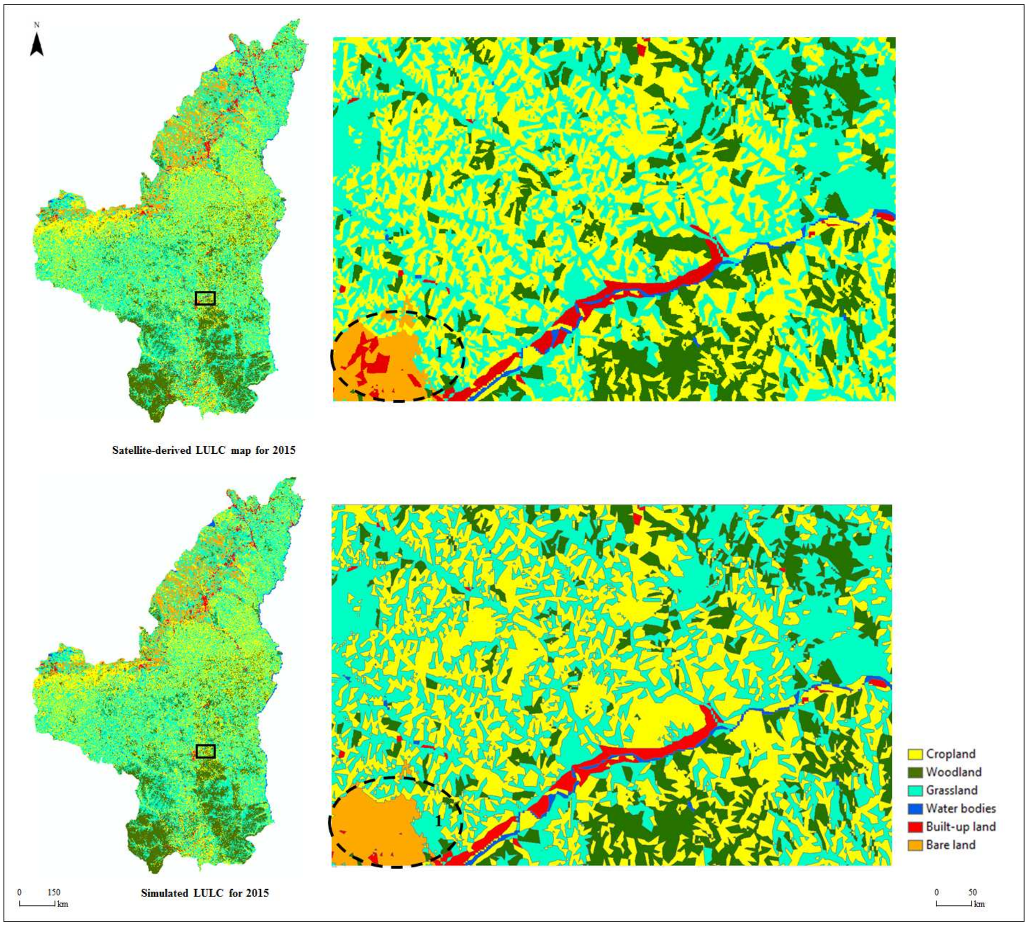

Figure 7- 1 Comparison of spatial distribution of the satellite-derived and simulated LULC for 2015

7.1.2 Simulation of LULC change patterns under different scenarios

The simulation results of LULC scenarios illustrate different LULC patterns in northern Shaanxi in 2050. Table 7-2 shows the area and percentage of LULC types under different scenarios. In all of the scenarios, grasslands are still the dominant LULC type in northern Shaanxi in 2050. Water bodies, built-up lands and bare lands have the smallest portion of the area in all scenarios.

- Under protection scenario, LULC change patterns are similar to the patterns from 2000 to 2015 (ERPs period). In this scenario, the simulation results indicate that the cropland area decreases from 31.42% in 2015 to 29.11% in 2050. Areas of woodland and grassland show an increase tendency. Areas of woodland increase from 15.31% in 2015 to 17.01% in 2050, while areas of grassland increase from 45.28% in 2015 to 45.72% in 2050. A comparison between the simulated scenarios in 2050 with LULC map in 2015 showed that the trend of woodland area increased by 1367 km^2, while grasslands slightly increase by 359 km^2. Thus, the afforestation process is supported and consequently cropland areas tend to decline with an 1839 km^2 decrease under this scenario.
- Under BAU scenario, LULC change patterns are similar to the patterns from 1988 to 2000 (pre-ERPs period), which means that croplands, woodlands and grasslands are expected to slightly increase. In this scenario, grasslands still accounted for the largest part (45.51 %). Croplands and woodlands accounted for 31.49% and 15.43%, respectively. A comparison between BAU scenario and LULC map in 2015 showed that woodlands grasslands, and croplands slightly increased. Areas of woodland and grassland increased by 0.12% and 0.23% respectively in 2050, while areas of cropland increased by 0.07% in 2050.
- Under No LULC change scenario, this scenario is to characterize the interactive roles of climate in the changes of water-related ES, especially for water yield changes. Current LULC map in 2015 is used in this scenario.

Compared with protection and BAU scenarios, croplands in protection scenario decreased by 1839 km^2, while woodlands in protection scenario increased by 1367 km^2. Areas of grassland, water body, built-up land, and bare land were similar in both scenarios.

Table 7- 2 Comparison of area of LULC type under three scenarios

LULC types	LULC scenarios in 2050					
	Protection		BAU		No LULC Change	
	km^2	%	km^2	%	km^2	%
Cropland	23256	29.11%	25150	31.49%	25095	31.42%
Woodland	13596	17.01%	12322	15.43%	12229	15.31%
Grassland	36526	45.72%	36349	45.51%	36167	45.28%
Water bodies	645	0.80%	666	0.83%	681	0.85%
Built-up land	1492	1.86%	1512	1.89%	1227	1.54%
Bare land	4370	5.47%	3872	4.85%	4472	5.60%

Areas of cropland, woodland, and grassland under different scenarios at sub-watershed scales are shown in Figure 7-2. Under protection scenario, the croplands in all sub-watersheds decrease from 2015 to 2050 (Figure 7-2a). The maximum cropland decrease appears in sub-watershed No. 20, with a decrease of 303 km^2 in 2050, while the minimum cropland decrease is sub-watershed No. 24, with a decrease of 5 km^2 from 2015 to 2050. As for woodlands, only woodlands in sub-watershed No. 23 decrease by 15 km^2 from 2015 to 2050, while woodlands in the rest of sub-watersheds show an increase tendency from 2015 to 2050. The maximum increase of woodland is the sub-watershed No. 20, with an increase of 241 km^2 from 2015 to 2050. Grasslands in most sub-watersheds increase from 2015 to 2050, while grasslands in five sub-watersheds (No.1, 4, 5, 9, 23. And 26) decrease, especially in sub-watershed No. 23, with a 177 km^2 decrease from 2015 to 2050.

Under BAU scenario, LULC change in the whole study site is characterized by gradual changes and less extreme development. LULC change in each sub-watershed also follow this LULC change pattern. Areas of cropland, woodland, and grassland in most sub-watersheds are similar in comparison to 2015. The maximum cropland increase is sub-watershed No. 18, with an increase of 81 km^2. Areas of woodland in sub-watershed No. 2 and 18 increase by 50 km^2 and 59 km^2 respectively, while it decreases by 58 km^2 in sub-watershed No. 23. The maximum grassland increase is sub-watershed No. 18, with an increase of 183 km^2 under this scenario.

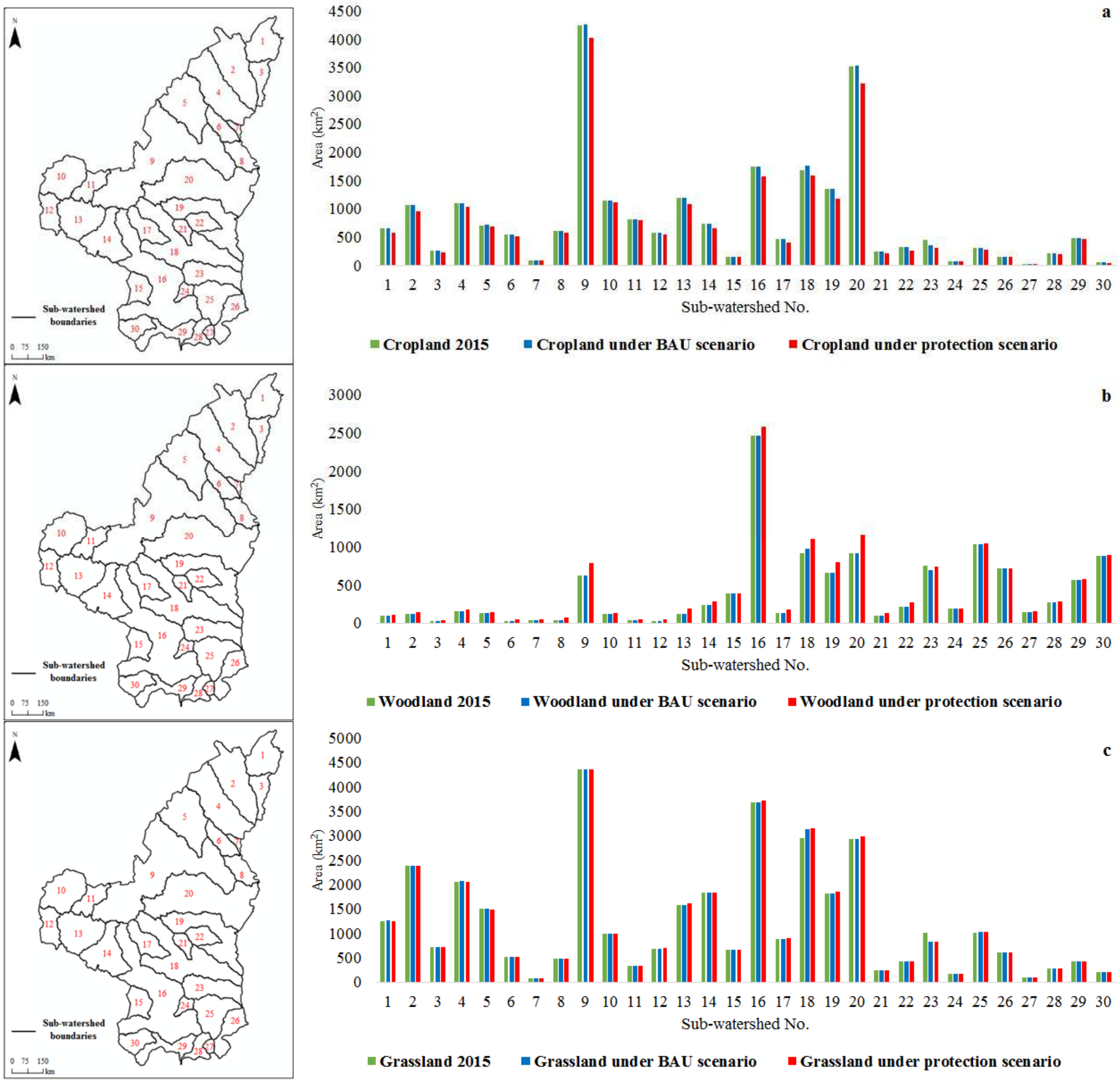

Figure 7- 2 Areas of cropland, woodland, and grassland under protection and BAU scenarios and the baseline year (2015) at sub-watershed scales. Sub-watersheds are numbered from 1 to 30.

7.2 Statistical downscaling the RCPs 4.5 scenario

7.2.1 Statistical downscaling model validation

The SDSM is trained and validated separately for downscaling temperature and precipitation. The SDSM is tested by downscaling historical conditions and then matching the results to our historical observational records. If this model can properly downscale the past, they are then run forward in time to downscale future scenario. In this study, the calibration is carried out from 1981-1991 and the withheld data from 1992-2001 is used for model verification. Two groups of results of surface climate variables are produced by SDSM for the cross validation (Figure 7-3 and 7-4).

As shown in Figure 7-3, the results indicate that there is a good agreement between the observed monthly mean maximum temperature (T_{max}) and monthly mean minimum temperature (T_{min}) and those driven by using NCEP predictors over the validation period. As for the monthly mean T_{max} variable, simulated monthly mean T_{max} in Summer and Autumn shows better performance than Spring and Winter among most stations. It is found that simulated monthly mean T_{max} in December is usually over-estimated. For instance, simulated monthly mean T_{max} in December in the station 53529 is 1.07 °C, while the observed monthly mean T_{min} in the same month and station is 0.39 °C. As for the monthly mean T_{min} variable, simulated monthly mean T_{min} in Autumn and Winter shows better performance than Spring and Summer among most stations. It is found that simulated monthly mean T_{min} in July is usually under-estimated. For example, simulated monthly mean T_{min} in July in the station 53529 is 12.7 °C, while observed monthly mean T_{min} in the same month and station is 16.8 °C. Although simulated monthly mean T_{max} and T_{min} results show over or under estimated, results of simulated monthly mean T_{max} and Tmin match observed data well with an average R^2 of 0.9 among all stations.

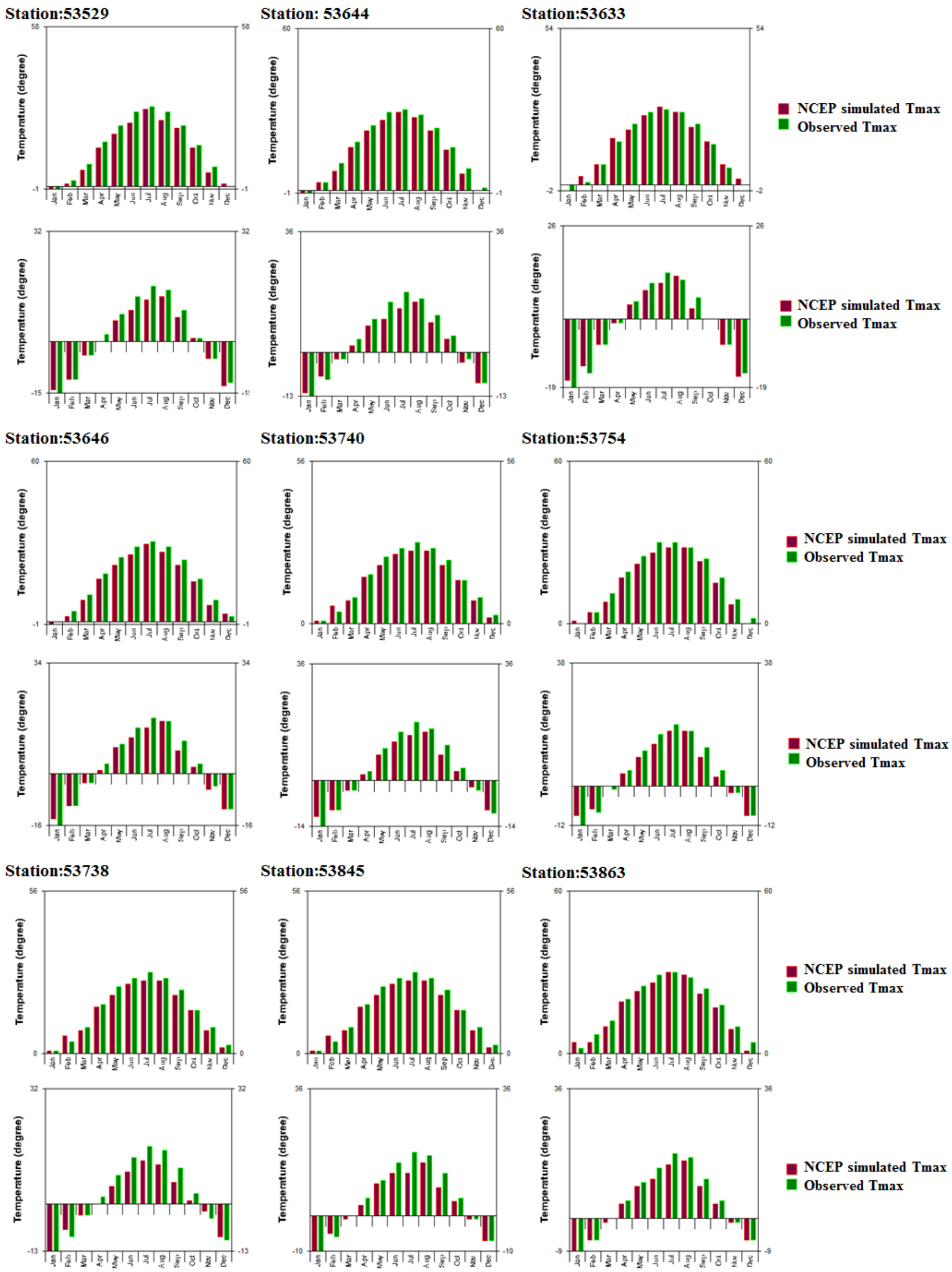

Figure 7- 3 Comparison between observed and downscaled NCEP monthly mean T_{min} (a) and T_{max} (b) for the validation period (1992-2001) at nine weather stations

Figure 7-4 presents the results of the validation at each weather station by giving the comparison between observed and downscaled NCEP monthly mean precipitation. During the validation period, the SDSM basically captured the main characteristics of the annual cycle of precipitation in northern Shaanxi, with a large amount of precipitation in summer and less precipitation in the other seasons. The best and the worst performances are observed at station 53740 (R^2= 0.86) and station 57034 (R^2= 0.36), respectively. Moreover, simulated monthly mean precipitation in most stations showed that precipitation was generally under-estimated by SDSM. For example, simulated monthly mean precipitation in August in the station 53754 is 2.94 mm, while observed monthly mean precipitation in the same month and station is 4.19 mm.

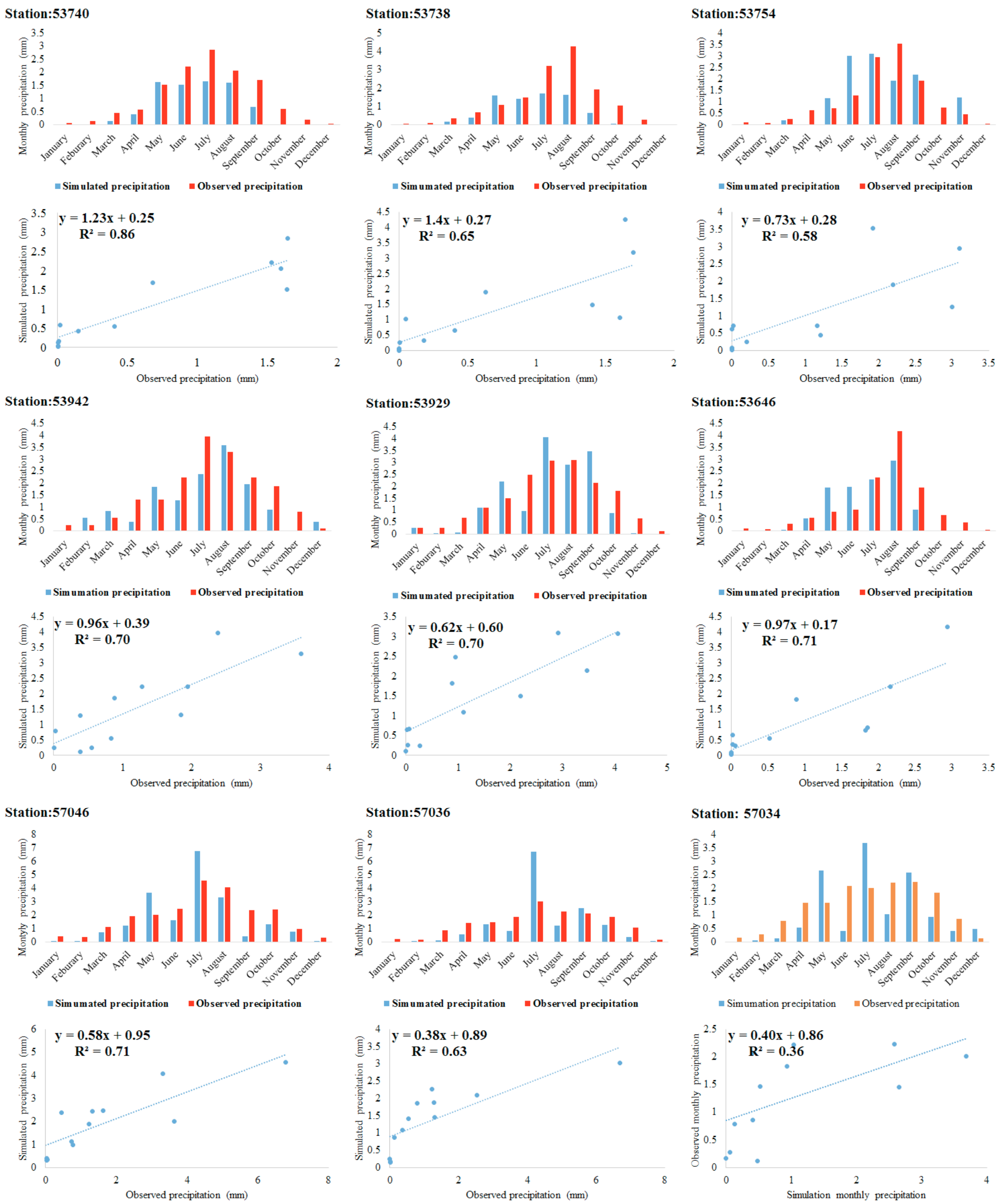

Figure 7- 4 Comparison between observed and downscaled NCEP monthly mean precipitation for the validation period (1992-2001) at nine weather stations

7.2.2 Statistical downscaling of the RCPs 4.5 scenario

After calibration and validation of the SDSM for the study site, the model is used to downscale precipitation and temperature (T_{max} and T_{min}) in the region for the periods of

2040-2050s under CanESM2 RCPs 4.5 scenario. All downscaled results are represented by the average annual unit (e.g. average annual precipitation). As shown in Table 7-3, it is found that there is a decrease tendency in average annual precipitation in all stations under Can ESM2 RCPs4.5 scenario in 2040-2050s period. The average downscaled precipitation during 2040-2050s (354.5 mm) is lower than the observed precipitation during 2000-2013s (485.4 mm). Average annual precipitation from 2040-2050s is lower than in the periods of 2000-2013s in all weather stations. Especially, average annual precipitation in station 53738 produces the largest decrease. It decreases by 210.3 mm from the periods of 2000-2013s to the periods of 2040-2050s.

Table 7- 3 Comparison between historical and downscaled average annual precipitation for each weather station

Station	**Average annual precipitation (mm)**		
	1988-2000s (observed)	**2000-2013s (observed)**	**2040-2050s (downscaled)**
53646	358.9	443.1	254.2
53738	443.8	470.0	259.7
53740	331.3	390.1	258.2
53754	407.7	445.1	369.0
53845	485.7	550.3	432.4
53929	564.4	628.0	462.9
53942	480.3	477.7	323.4
57036	490.1	490.3	369.1
57046	406.2	474.3	461.8
Average	440.1	485.4	354.5

The results are summarized in Table 7-4 and Table 7-5 which show the downscaled and observed maximum and minimum temperatures in nine weather stations. As shown in Table 7-3, downscaled average annual T_{max} shows a little variation among all weather stations under CanESM2 RCPs 4.5 scenario. Downscale average T_{max} among all weather stations during 2040-2050s (15.8°C) is slightly lower than the observed T_{max} during 2000-

2013s (16.5 °C). As shown in Table 7-4, downscaled average annual T_{min} shows a slightly decrease tendency in all weather stations compared with the period of 2000-2013s. Downscaled average T_{min} among all weather stations during 2040-2050s decreased by 0.8 °C in comparison to the period of 2000-2013s.

Table 7- 4 Comparison between historical and downscaled average annual maximum temperature for each weather station

Station	**Average annual maximum temperature (°C)**		
	1988-2000s (observed)	**2000-2013s (observed)**	**2040-2050s (downscaled)**
53646	16.1	15.9	15.6
53738	15.9	16.4	15.5
53740	16.3	16.8	15.7
53754	16.8	16.9	16.3
53845	17.5	18.1	17.0
53633	13.4	13.6	14.8
53644	16.1	16.3	15.3
53863	17.9	18.1	17.5
53942	15.7	16.2	14.9
Average	16.2	16.5	15.8

Table 7- 5 Comparison between historical and downscaled average annual minimum temperature for each weather station

Station	**Average annual minimum temperature (°C)**		
	1988-2000s (observed)	**2000-2013s (observed)**	**2040-2050s (downscaled)**
53646	2.2	3.6	1.9
53738	2.2	2.2	1.8
53740	3.1	3.1	3.1
53754	4.5	4.6	4.6
53845	4.7	5.3	3.9

53633	-1.75	-0.8	-1.3
53644	3.7	4.3	2.8
53863	4.7	5.5	4.5
53942	5.0	5.5	4.7
Average	3.2	3.7	2.9

Table 7-6 shows the downscaled and observed average annual temperature in nine weather stations. Global temperatures averaged over the period 2081– 2100 are projected to likely exceed 1.5°C above 1850-1900 for RCPs 4.5 scenario (Collins et al., 2013). In this study, it is found that the local mean temperature changes from 2000- 2013 to 2040-2050 periods in all weather stations ranges from -0.35 to -1.35 °C. The downscaled average temperature among nine weather stations is 9.4 °C which is 0.7 °C lower than that in the present era 2000-2013s.

Table 7- 6 Comparison between historical and downscaled average annual temperature for each weather station

Station	**Average annual temperature (°C)**		
	1988-2000s (observed)	**2000-2013s (observed)**	**2040-2050s (downscaled)**
53646	9.2	9.8	8.7
53738	9.1	9.3	8.6
53740	9.7	10.0	9.4
53754	10.7	10.8	10.5
53845	11.1	11.7	10.4
53633	5.8	6.4	6.7
53644	9.9	10.3	9.1
53863	11.3	11.8	11.0
53942	10.4	10.9	9.8
Average	9.7	10.1	9.4

After downscaled the minimum and maximum temperatures in the periods of 2040-2050s under RCPs 4.5 scenario, ET_0 in the same period is estimated by the HS model. Table 7-7 presents average annual ET_0 in different weather stations in three different time periods. The average ET_0 among nine weather stations in the periods of 2040-2050s is slightly lower than the average ET_0 in the period 2000-2013s. However, annual ET_0 varies from one weather station to another. For example, annual ET_0 in station 53663 increases by 10% in comparison to the periods of 2000-2013s, while it decreases by 8% in station 53942. In 2040-2050s, the highest ET_0 appears in the weather station 53863, reached at 1015.3mm, while the lowest ET_0 appears in the weather station 53942, reached at 963.0 mm.

Table 7- 7 Comparison between historical and downscaled *ET0* for each weather station

Station	**Average annual ET_0 (mm)**		
	1988-2000s (observed)	**2000-2013s (observed)**	**2040-2050s (downscaled)**
53646	952.1	910.5	944.6
53738	946.1	969.1	958.6
53740	953.3	974.8	934.4
53754	953.8	957.9	940.0
53845	992.1	1008.4	1005.0
53663	858.4	854.2	941.3
53664	917.0	912.6	912.7
53863	1020.1	1016.3	1015.3
53942	904.4	917.5	842.4
Average	944.4	946.8	943.8

Figure 7-5 shows the spatial distribution of downscaled and observed average annual precipitation (a) and ET_0 (b) in three different time periods in northern Shaanxi. As shown in Figure 7-5a, the downscaled precipitation basically captured the main characteristics of the spatial distribution of precipitation in northern Shaanxi, with a decrease from south to north. It is found that the downscaled precipitation in the south regions is lower than the observed precipitation in the period of 2000-2013s. As shown in Figure 7-5b, during the period 2040-2050s, the south regions show the lowest ET_0 in the period of 2040-2050s.

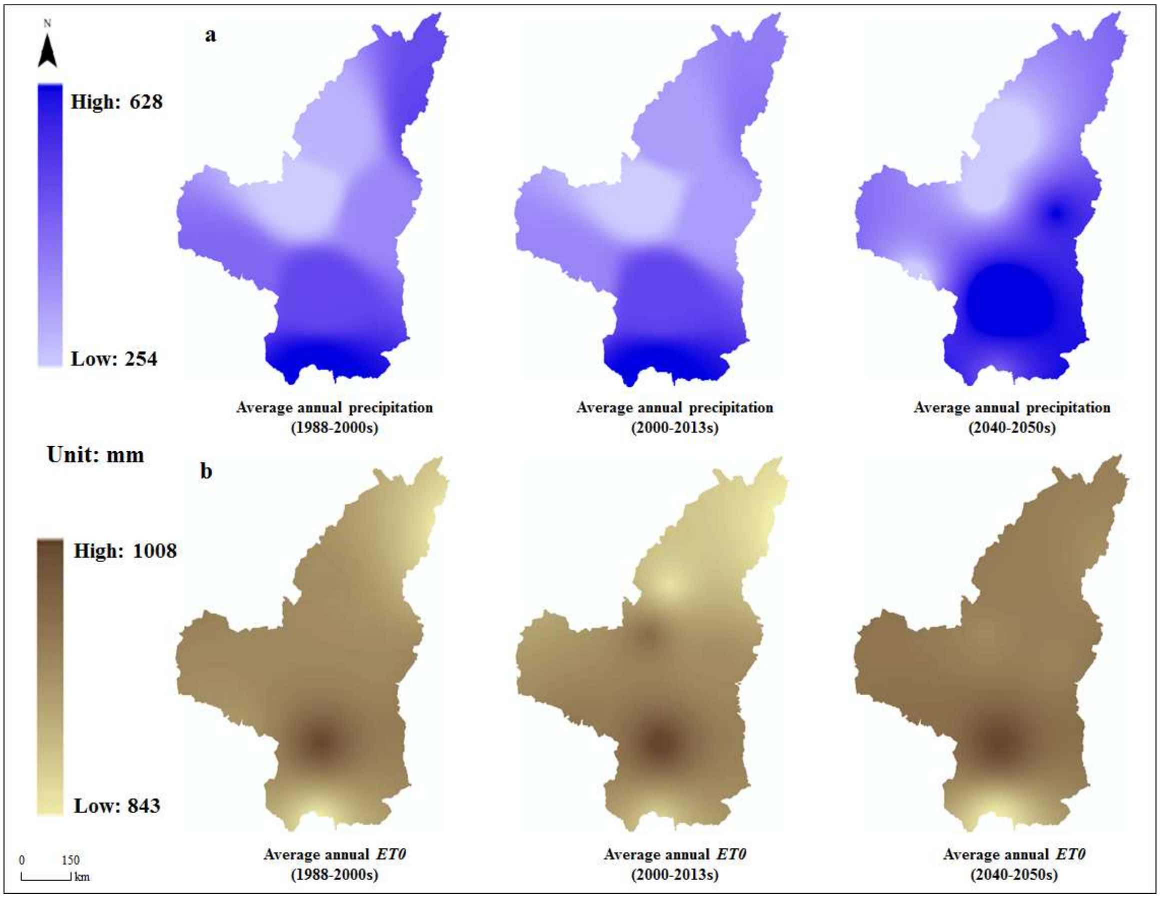

Figure 7- 5 Spatial distribution of average annual precipitation (a) and ET_0 (b) in northern Shaanxi in three different time periods

7.3 Scenario analysis

7.3.1 Soil erosion values and their changes under different scenarios

Table 7-8 shows the annual soil erosion under three scenarios. Under protection and BAU scenarios, soil erosion shows a decrease tendency in comparison to the year of 2015 in northern Shaanxi. However, the total soil erosion shows a little difference under these two scenarios. Soil erosion under protection scenario is 0.684 billion tonnes, while soil erosion under BAU scenario is 0.686 billion tonnes. It should be noted that soil erosion under No LULC change scenario is actual soil erosion map in 2015 because the rainfall erosivity factor was not simulated under the climate change scenario. This is because rainfall erovisity is calculated from daily rainfall more than 12 mm. It is difficult to simulate accurately precipitations in the future (Walsh et al., 2008; Willems and Vrac 2011).

Table 7- 8 The annual soil erosion under different scenarios in northern Shaanxi

	2015	**LULC change scenarios**		**No LULC change scenario**
Soil erosion		Protection	BAU	
(billion tonnes)	0.766	0.684	0.686	0.766

Figure 7-6 shows the spatial distribution of soil erosion under three scenarios. It should be noted that the spatial distribution map of soil erosion under No LULC change scenario is actual soil erosion map in 2015 because the rainfall erosivity factor was not simulated under the climate scenario. The results indicate that there are not significant spatial variations of soil erosion under protection and BAU scenarios. But compared with soil erosion in 2015, there are significant spatial variations of soil erosion. As shown in Figure 7-6 and Figure 7-7, the majority of soil erosion changes occur at severe soil erosion level. It accounts for 16% of total area in 2015, while it decreases to 11% of total area under protection scenario and 10% of total area under BAU scenario, respectively. The main decrease of severe soil erosion appears in the central regions in both scenarios. However, the southwest and north regions are still severe soil erosion level under both scenarios. Moreover, areas of intensive level increase from 21% of total area in 2015 to 28% of total area under protection and 29% of total area under BAU scenarios. The major expansion of intensive soil erosion occurs in the central-west and south regions in both scenarios. It also expands in north regions which was the areas of very intensive soil erosion level. Areas of very intensive level slightly decrease from 52% of total area in 2015 to 50% of total area under BAU scenario and 49% of total area under protection scenario.

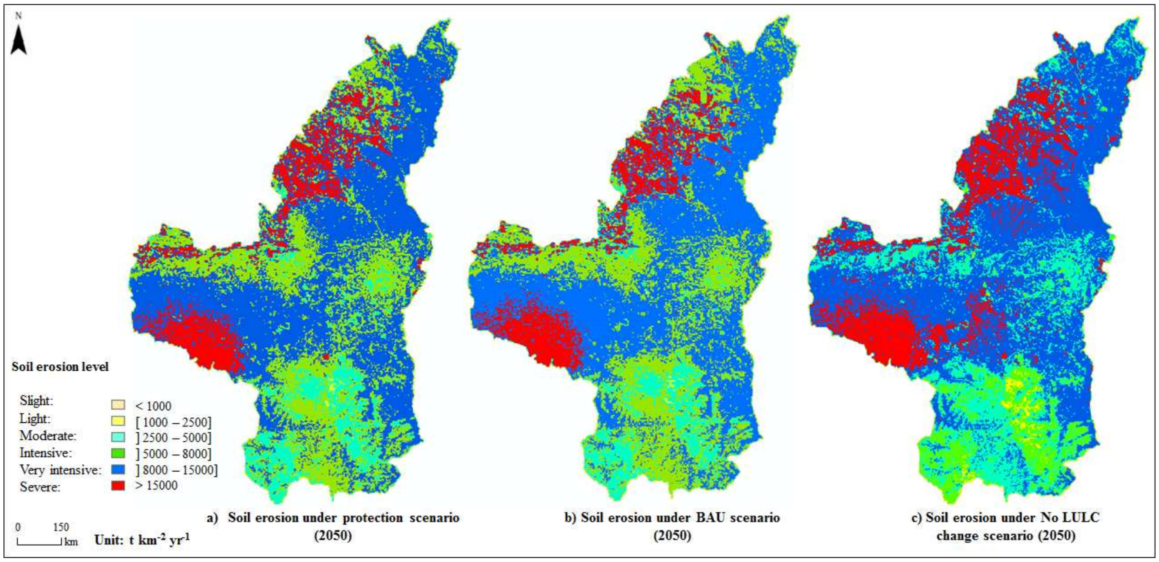

Figure 7- 6 Spatial distribution of soil erosion in northern Shaanxi under different scenarios

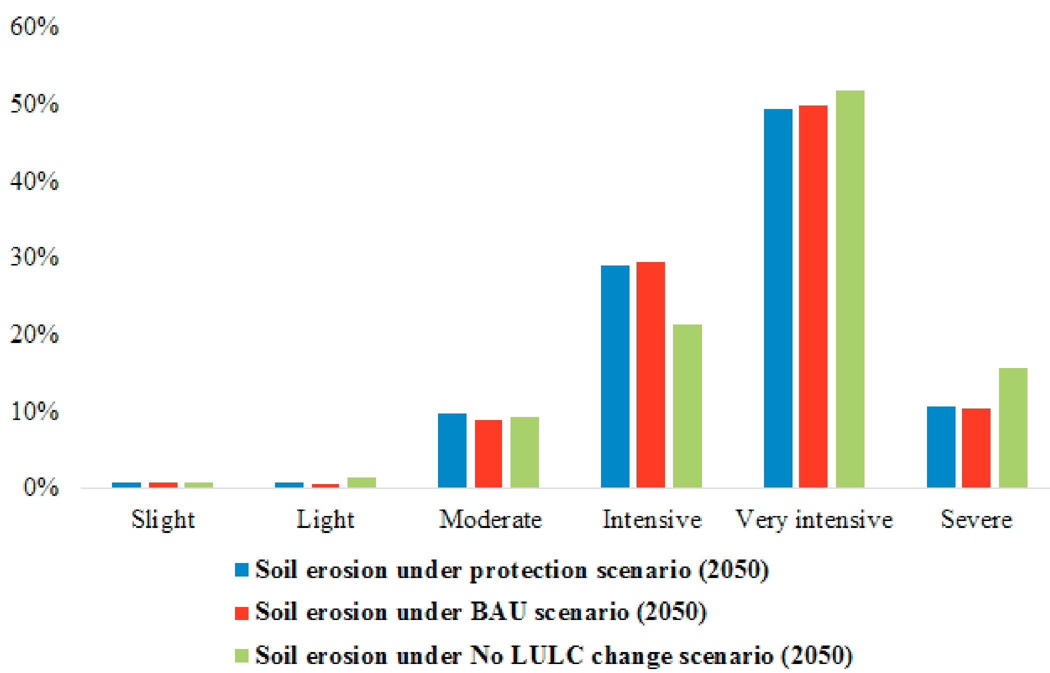

Figure 7- 7 Percentage of soil erosion level in northern Shaanxi under different scenarios

7.3.2 Water yield values and their changes under different scenarios

Compared with the year of 2015, the average water yield among thirty sub-watersheds shows a decrease tendency under three scenarios in northern Shaanxi (Table 7-9). Water yield would decrease by as much as 28% (No LULC change scenario) to 37% (protection scenario). The lowest average water yield appears in protection scenario (3.69 billion m^3), while the highest appears in No LULC change scenario (4.22 billion m^3). The average water yield decreases by 2.17 billion m^3 under protection scenario, while the average water yield decreased by 1.7 billion m^3 under BAU scenario. Under No LULC change scenario, the average water yield decreases by 1.64 billion m^3.

Table 7- 9 The average water yield among thirty sub-watersheds in northern Shaanxi

	2015	**LULC change scenarios**		**No LULC change scenario**
		Protection	BAU	
The average water yield among thirty sub-watershed (billion m^3)	5.86	3.69	4.16	4.22

Figure 7-8 shows the amount of water yield in thirty sub-watersheds in northern Shaanxi. Water yield in each sub-watershed shows almost similar values under BAU and No LULC change scenarios. However, water yield in each sub-watershed under these two scenarios is higher than protection scenario. Moreover, under three scenarios, water yield in twenty-seven sub-watersheds show a decrease tendency in comparison to the baseline year (2015). The highest value of water yield is always sub-watershed No. 16, with 0.52 billion m^3 (protection scenario), 0.58 billion m^3 (BAU scenario), and 0.59 billion m^3 (No LULC change scenario). The lowest value of water yield is sub-watershed No. 7, with 0.1 billion m^3 (three scenarios). In contrast to water yield in 2015, the highest water yield decrease appears in the sub-watershed No. 29, with decreases rates up to 68% (protection scenario), 64% (BAU scenario), and 63% (No LULC change scenario, respectively. Water yield in the sub-watershed No. 19 increases by 13% (protection scenario), 28% (BAU scenario) and 30% (No LULC change scenario), which is the highest water yield increase among thirty sub-watersheds.

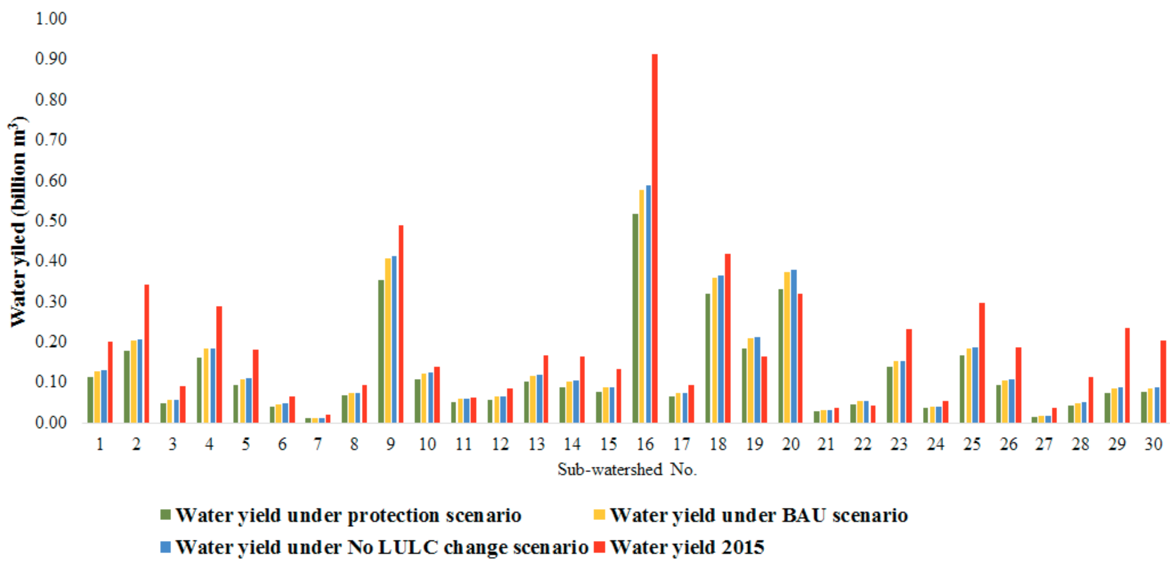

Figure 7- 8 The average water yield per sub-watershed in northern Shaanxi under different scenarios

7.4 Discussion

7.4.1 Potential impacts of ERPs on water-related ES under different scenarios

This section analyses the potential impacts of ERPs on water-related ES under different scenarios. It integrates an understanding of what level of the ERPs should be maintained in northern Shaanxi. The scenario analysis is not an absolute measure of water-related ES changes, but different scenario designs that allow a number of management options to be compared objectively. Our application is significant because it evaluated the potential impacts of the ERPs on water-related ES in semi-arid and arid regions, which had rarely been addressed in the literature.

Our findings on the three scenarios firstly reveal that the ERPs are likely to be continued as important and influential on soil erosion in 2050. These results are expected because an increase of forest and grassland will protect the surface from falling rainfall and disperse their energy (Agnese et al., 2011; Archer et al., 2013). In this study, the USLE model has been used to calculate soil erosion rate, and the parameters of soil erodibility, slope length-steepness, erosion control practices factor were assumed that they did not change in the future. Rainfall erovisity in 2015 was employed to calculate soil erosion in

2050. Thus, vegetation cover management factor calculated from LULC types is the only variation parameter for scenario analysis.

Water yield would decrease by 28% (No LULC change scenario), 29% (BAU scenario), and 37% (protection scenario). This result reveals that the ERPs are likely to be continued as important and influential on the provision of water in 2050. Water yield under three scenarios implies the hydrological consequences of LULC changes, especially under protection scenario. However, water yield under BAU and No LULC change scenarios show a little different value, demonstrating that climate factors (e.g. precipitation and ET_0), ecological restoration and their interactions were likely to place substantial pressures on the provision of water by 2050. Precipitation and LULC change are key drivers to the change of water yield in the Loess Plateau (Feng et al., 2017; Li et al., 2017). Precipitation determines how much water is provided by nature, it is the LULC that determines the amount of water converted to water yield and water storage. LULC change can modify hydrological regimes of evapotranspiration, infiltration and water retention, and the water available to rivers and ground water resources (Sanchez-Canales et al., 2012; Bangash et al., 2013). Several recent studies have analysed the complexity of human activities in shaping runoff in the Loess Plateau under a changing climate for a long-term period. Feng et al. (2017) identified the roles of human activities (e.g. the ERPs) in runoff trends and their interaction with climate factors (e.g. precipitation) in the Loess plateau from 1961 to 2009. Their results indicated that reduced precipitation was the dominant factor causing reduction in runoff over the entire study period, while water provision decreased after human intervention, such as implementation of ERPs. However, modelling by Sun et al. (2006) in China showed that annual runoff reduction due to reforestation can be up to 50% in the semi-arid Loess Plateau regions while the reduction is only 30% in tropical southern regions. Moreover, a statistically significant climatic drying starting from 2000 (Zhang et al., 2015). Zhang et al. (2016) suggested that the water yield decrease in the Loess Plateau in the 2000s could be attributed to both climate aridity and afforestation in this region. These findings above suggest that the sensitivity of water yield to vegetation cover change is not constant but may vary along climatic gradients (Donohue et al., 2011).

It was found that soil erosion and water yield decreased due to large-scale afforestation in this study, and it is widely recognized that vegetation restoration plays a key role in controlling soil erosion in China's Loess Plateau (Fu et al., 2011; Jia et al., 2014; Sun et al., 2014). Water is one of the most important factors for large-scale afforestation and social economic development in semi-arid and arid regions, like the Loess Plateau. However, trade-offs existed in soil erosion and water yield, which means an improvement in erosion service is achieved at the expense of a decrease in the provision of water in northern Shaanxi. Previous studies have noticed that current level of the ERPs might need to be modified in semi-arid and arid regions (Chapter 5 and 6, this study; Cao 2008; Xu 2011). Thus, 'the best scenario' is to decrease soil erosion at less expense of decrease of the provision of water. Our scenario results indicate that the ERPs are likely to place substantial pressures on the provision of water by 2050 under protection scenario, while soil erosion simulation results show a little difference under both protection and BAU scenarios. Protection scenario is designed to be similar to the ERPs period (2000-2015), while BAU scenario is designed to be similar to the pre-ERPs period (1988-2000). These results suggest that current ecological restoration practices might support soil and water conservation in the future in northern Shaanxi. In other words, even without large-scale afforestation in this region, current areas of woodland and grassland might support the soil and water conservation in the future.

Moreover, it was also found that spatial heterogeneity of relationships between LULC and soil erosion existed in northern Shaanxi. The GWR analysis results also indicated that croplands and grasslands played an important role in controlling soil erosion compared to woodlands. Especially, dense grasslands are more effective in controlling soil erosion. However, increasing of woodland had negative impacts on water yield. Therefore, promoting the development of grassland is the key for vegetation to conserve soil and water in this area. Our statistical downscaling results also indicate that downscaled precipitation in the period of 2040-2050s are lower than the period of 2000-2013s. Vegetation can be changed as time goes by. Thus, relationships between soil erosion and LULC across different sub-watersheds might be modified because related parameters (e.g. precipitation and vegetation) are changed. Long-term monitoring and assessment of water-related ES in this region is necessary.

7.4.2 Uncertainties of scenario design

The scenarios illustrate plausible futures that can guide comprehensive decision-making for future ERPs developments. But determining ecosystem restoration needs should be at the strategic level (Kondolf et al., 2011). To make restoration activities successful and sustainable, the variety of stressors including natural and social factors need to be taken into account when devising restoration measures both for different physiographic conditions and also for specific local contexts (Nagendra 2007). Local and national objectives also need to be connected to the goals of different stakeholders, as is actively linking restoration science with local aspirations and practices so that national ERPs achieve their social and environmental goals (Chen and Sturtevant 2012; Van Oosten et al., 2014). Moreover, monitoring the ERPs is an essential component of tracking progress and taking corrective measures (Dey and Schweitzer 2014). In this study, we only analyse the impacts of the ERPs on water-related ES under different LULC scenario and RCPs 4.5 climate scenario. Stakeholders' benefits and social factors, i.e. livelihoods of local residents, are not considered in this study due to data limitation. Further studies should integrate social factors into the ERPs assessment and long-term monitoring and assessing the ERPs is necessary.

Likewise, estimates of LULC and climate change impacts on soil and water require integrated use of land, climate, soil, and hydrology models. In arid and semi-arid regions where precipitation is an important environmental factor, the variation of precipitation can have a significant impact on the local ecological systems (Lioubimtseva et al., 2005). The change of precipitation is expected to alter surface evaporation, transpiration, and soil water content, which in turn can have an influence on water yield in a watershed and hydrologic budgets across broad spatial scales (Wullschleger and Hanson, 2006). Assessing the ultimate consequences of LULC and climate change effects requires detailed assessments at every step in the impact chain from climate through to land, soil and hydrological modeling. In this study, firstly, the SDSM is employed to downscale the CanESM2 outputs. The historic simulation of precipitation shows a middle agreement (average R^2 among nine weather station = 0.66) when compared against observed precipitation in independent evaluation periods. It is also found that simulated monthly mean precipitation in most stations is generally under-estimated by SDSM. Secondly, only

RCPs 4.5 intermediate emission scenario was downscaled. This scenario is a scenario that stabilizes radiative forcing level at 4.5 Wm^{-2} in the year 2100 without ever exceeding that value. The low emission and high emission scenarios are not considered. Moreover, the uncertainties existed in LULC change modeling. Thus, the uncertainties of statistical downscaling and LULC change modeling might affect the accuracy of the ERPs impact assessment on soil erosion and water yield.

7.4.3 Uncertainties of LULC planning scenarios

Understanding future LULC change is a core for science-directed sustainable management of the LULC resources and ecosystem management. However, the theoretical LULC distributions generated through the Markov_CA model revealed different trends, under different scenarios we designed. It must again be emphasized that the Markov_CA values do not represent realistic future states for northern Shaanxi. LULC scenarios designing in this area are a reflection of the policy towards better soil and water conservation. In this study, using historical LULC and their associated driver datasets, LULC changes for the next thirty-five years in northern Shaanxi are simulated. Three kinds of scenario, i.e. protection, BAU and No LULC change scenarios are designed. The simulated LULC change in this study are spatially explicit, and also provide a representation of the entire landscape, i.e. modelling all major LULC types of the study site. Our approach, thus, overcomes the limitations of other simulation modelling studies that examine only a specific part of LULC types. However, Hou et al. (2013) indicated that most spatial models contain a high level of uncertainty. The difficulties of LULC scenario are related to qualitative interpretation and also to the level of detail and the precision or availability of spatial information (Mancosu et al., 2015). The model's limited capacity to simulate natural phenomena (e.g. climate change) and computing limitations still represent a challenge in LULC modelling and simulation (Verburg et al., 2008; Dong et al., 2018). The Markov_CA model is validated using the satellite-derived map LULC map of 2015 and showed an overall accuracy of 84.64%. However, compared with each LULC class under simulated and satellite-derived land map for 2015, it is found that , grasslands and built-up lands in the simulated map for 2015 represented a less good fitness with the satellite-derived map for 2015. This reveals that although more similarity is found between the simulated result and the actual LULC in 2015, it still exhibits a certain bias.

It should be pointed out that the simulation approach of this study only addressed the future LULC changes based on the considered scenarios, which were developed either empirically generated datasets or assumptions as followed by previous studies (e.g. Liu et al., 2017; Zare et al., 2017). Information about the role of driving forces of LULC change is most obtained from empirical comparative studies (Veldkamp et al., 2001). But this emphasises the need for improved validation of empirical models. If data requirements could be met, process-based models could be applied to produce quantified estimates of LULC changes. Moreover, LULC change is more than the product of human behavior only, for it is intimately tied to the physical environment. Similar social, political, and economic conditions of decision making in dissimilar physical environments usually yields different land uses. In this study, statistical downscaling results of precipitation and ET_0 in the period of 2040-2050s are not used as the drivers in the LULC scenario simulation because these two parameters are independently used to analyse the impacts of the future precipitation and ET_0 on water-related ES, especially on water yield under No LULC change scenario. However, LULC change can result in the emissions of greenhouse gases that cause climate change. Climate change also affects the productivity of land, which in turn leads to further LULC change (Mendelsohn and Dinar 2009). Thus, we suggest that future studies pay much attention on potential LULC change consequences in response to climate changes.

7.4.4 Uncertainties of statistical downscaling

The historic simulation of temperature shows a high agreement when compared against observed temperature in independent evaluation periods. These results imply that the downscaled temperature data not only represent high-spatial-resolution climate trends but are also more reliable than the CanSEM2 raw data for studying climate trends. However, it is found that the simulation results of temperature are better than the precipitation simulation during the validation period. In general, computer models which try to mathematically simulate the climate are essential tools for estimating the responses to ongoing and future drivers, as well as for exploring potential feedbacks and sensitivities (Gonzalez et al., 2010). These models usually include the representations of relevant physical, dynamical, and chemical processes. However, given complex interactions between the atmosphere, cryosphere (e.g. ice), hydrosphere (e.g. oceans), lithosphere (e.g.

land), and biosphere (e.g. life), understanding the climate response to the resulting anthropogenic forcing and the interactions between climate change, atmospheric chemistry feedbacks, and transport processes is still a major challenge (Stute et al., 2001). Currently, it is generally difficult to simulate climate change accurately into the future, especially in terms of precipitation (Walsh et al., 2008; Willems and Vrac 2011).

In particular, this is mainly due to the conditional nature of precipitation. There is an intermediate process between regional forcing and local weather. Local precipitation depends on the rainfall occurrence, which in turn depends on regional-scale predictors such as humidity and atmospheric pressure (Wilby and Dawson 2004). Moreover, the SDSM remains unchanged in the downscaling as time progresses, which means its projected temporal structure of future climatology remains identical to the baseline (Diaz-Nieto and Wilby, 2005). It is difficult to select an appropriate combination of predictors for SDSM due to inherent characteristics of seasonality, topography, and the complexity of local microclimates (Aavudai et al., 2008).

We did not find many papers which have downscaled annual precipitation and ET_0 in northern Shaanxi, but there are several studies which have analysed precipitation and ET_0 in the Loess Plateau and the national scale. Thus, we make the comparison between our findings and those of the previous studies in the Loess Plateau and China. Based on our downscaling results, firstly, the annual precipitation in northern Shaanxi will significantly decrease under RCPs 4.5 scenario during 2040-2050s period. This finding is not always consistent with previous studies. Tian et al. (2015) analysed the future tendency in precipitation over China under three RCPs scenarios and found that the annual mean precipitation would increase by 8% under the RCPs 4.5 scenario by the end of the 21st century. Wu et al. (2015) also pointed out that a general increase in precipitation in the range of 10%–25% or more was found over the northern part of China. Wang and Chen (2014) predicted that the average annual precipitation over the Loess Plateau would increase by 10% by the end of the 21st century. Secondly, the annual ET_0 in northern Shaanxi shows a non-significant decreasing trend under RCPs 4.5 scenario during 2040-2050s period. This finding is consistent with previous studies (Gao et al., 2017; Sun et al., 2018).

Our downscaled results indicated that the downscaled precipitation in the period of 2040-2050s are lower than the period of 2000-2013s. The projected climate data are from different sources and the downscaling methods are also different between our research and that of Tian et al. (2015) and Wu et al. (2015) which may explain the conflicting conclusions in different studies. Moreover, this might be caused by the CanSEM2 model. Stott et al. (2013) combined multiple climate models (e.g. CanSEM2 and CNRM-CM5) into a single synthesized estimate of future warming rates consistent with past temperature changes. They found that the CanESM2-based analyses gave much lower rates of possible warming in comparison to the multi-model average based estimates of future warming under RCPs 4.5 scenario.

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Chapter 8 General discussion and conclusions

The overall goal of this study is to analyse the impacts of ERPs on water-related ES, namely soil erosion and water yield, in a semiarid region- northern Shaanxi, China, in the long-term period. This assessment is based on an analysis framework including four aspects: (1) LULC change analysis; (2) water-related ES analysis; (3) relationship analysis; and (4) scenario analysis.

8.1 General discussion

The field of ecological restoration has experienced advancement and is now widely recognized as an essential component of the fields of conservation and sustainability (SER 2004). Ecological restoration projects are being implemented at a variety of scales and in a variety of contexts around the world, such as the United Nations Programme on Reducing Emissions from Deforestation and Forest Degradation (UN-REDD) programs, the European Union (EU) 2020 Biodiversity strategy, and the GGP. However, many projects meet with limited success due to inappropriate planning and implementation, a lack of appropriate effort or resources, or insufficient knowledge and skill (Jackson and Hobbs, 2009; Polasky et al., 2011; Suding 2011). There has been a growing need for a clear set of standards to establish benchmarks for the technical application of restoration treatments across ecosystem types, and to maximize ecosystem recovery within a framework that engages stakeholders (McDonald et al., 2016). In this thesis, Chapter 2 focused on how and to what extent have ES approaches been used to assess ERPs in China, which can provide insights into the ecological knowledge required for successful restoration.

It is well known that human activities, and in particular LULC change, have a significant effect on ecosystems and provision of ES (Baral et al., 2013; Fu et al., 2015). The issue of scale is also a fundamental attribute that explains the patterns and processes of ES (Raudsepp-Hearne and Peterson, 2016). ES can be affected by different social-ecological processes, and only at a certain scale a specific service can play a significantly dominant role (Andersson et al., 2015). Likewise, the development of effective nature conservation and environmental management policies requires a sound understanding of all the driving forces involved in natural and human society (Tzanopolos et al., 2013). Human activities which operate at multiple levels of the administrative scale may show non-linearity across scales (Cash et al., 2006), while geographical information can be represented differently depending on the scale of analysis (Syphard et al., 2011). Moreover, studying the temporal changes of ES supply is important given that ecosystems and their capacity to supply ES, as well as the demand for ES may change over time. Thus, temporal-spatial analyses based on multiple scales are essential to understand what makes a driver force scale sensitive (Tzanopolos et al., 2013) and reduce mismatches between the scale at which drivers operate and at which they are addressed by policies (Cumming et al., 2006).

In previous studies which evaluated the impacts of ERPs on ES, most studies have focused on modelling ES at a certain scale, such as field, regional or national scales. Then, these studies compared the values of ES before and after the implementation of the ERPs. However, comparisons of ES and their relationships at different scales or across scales are rare. This study quantified the changes of LULC, soil erosion and water yield from the pre-ERPs period to the ERPs period, analysed the relationships among LULC, soil erosion, and water yield at pixel-based scale and sub-watershed scale, and analysed the relationship between soil erosion and water yield at sub-watershed scale. Our study showed that spatial heterogeneity existed in different sub-watersheds. In particular, croplands not always decreased, and woodlands and grasslands not always increased during the ERPs period (Chapter 4). Soil erosion in some sub-watersheds increased even during the ERPs period (Chapter 5). The relationship analysis results indicated that the changes of soil erosion and water yield were caused by multiple drivers and that the ERPs might not always help soil and water conservation in northern Shaanxi (Chapter 6). This spatial heterogeneity can thus influence the efficiency of the ERPs on soil and water conservation depending on the sensitivity of the drivers (e.g. LULC) and the scale-matching of policies and management.

The presence of scale sensitivity has important implications for policy making (Cumming et al., 2006). The ERPs are considered as a "Top-Down" policy, which means generally addressed in sectoral policies that operate at large scale (e.g. national scale). In contrast, the existence of a clear scale sensitivity of the ERPs has a high relevance for regional or local policies based on specific geographical and social conditions. This phenomenon advocates for flexibility and a degree of autonomy in regional or local decision making for the ERPs. Or the ERPs could also support targeted actions adapted to local contexts. However, the contrasting scales of approach (pixel-based and sub-watershed scales) shown here, presents different data challenges. Data provided by the community relevant to LULC classification maps, soil data and topographical data as well as climate data are all key parts of the USLE and InVEST water yield models. Modelling parameters used were constrained by the relationship validation among LULC, soil erosion and water yield at sub-watershed scale in this study. Although the GWR analysis provided the detailed site information on the relationships between different LULC and water-related ES, the lack of consistent data available (e.g. forest attributes and soil moisture) at sub-watershed scale is a major constraint to mapping and analysing other drivers across multiple scale levels. Thus, it is difficult to accurately validate spatial heterogeneity in this study, and only a rough validation estimated in this study.

This study systematically evaluated effects of the ERPs on water-related ES in a long-term period. How the changes in vegetation affected soil erosion has been conducted in the field scales in the Loess Plateau (e.g. Huang et al., 2006; Wang et al., 2016; Feng et al., 2016; Ai et al., 2017). However, few studies have been conducted to examine spatial varying relationship between vegetation and soil erosion in large spatial scales. A proper methodology framework was established, which provided a practical methodology framework to represent effects of the ERPs on water-related ES at multiple spatial scales. Generally, process-based models are the obvious approach to estimate ecosystem values accurately, but these models are data-intensive, requiring detailed measurement of factors not easily obtainable, such as climate (e.g. wind speed and direction, humidity and sunshine hours), and soil (e.g. bulk density and various soil profile hydrological properties) data. This causes them to fit in with difficulty in the spatial modelling of regional or large spatial areas. However, the use of ecosystem empirical models (e.g. USLE) to predict absolute values is restricted by a lack of full verification. In this study, we compared our results with the newest available quantification results for water-related ES in the Loess Plateau and the integrated national ecological maps produced from national programs. Our results are in line with many papers (e.g. Fu et al., 2011; Su and Fu, 2013, Li et al., 2016; Liu et al., 2016).

Moreover, in previous studies which evaluated the impacts of ERPs on ES, multiple spatial evaluations have commonly been limited by the spatial resolution of the available data (this study, Section 2.3). Usually, modelling at finer scales demands more detailed data in order to predict outcomes effectively, while at larger scales statistical patterns become more regular and the use of coarser proxies more rational (Levin, 1992). Finer scale data which can show more detail for the subjects are usually obtained from the field samples, while large scale data (e.g. land use) are usually available on a grid basis. There is a lack of cross-scale datasets.

8.2 Major findings

This thesis provides a systematic methodology for assessing the impacts of the ERPs on water-related ES and analysed 1) the temporal and spatial changes of LULC, soil erosion, and water yield during the pre-ERPs and ERPs periods; 2) the spatial distribution of relationship pattern among LULC, soil erosion and water yield at sub-watershed scale; 3) the relationship between soil erosion and water yield; 4) the potential impacts of the ERPs on water-related ES in 2050.

Chapter 2 focused on how and to what extent have ES approaches been used to assess ERPs in China. The highlights include:

1) Current ERP assessment studies don't cover all ES categories equally. Most papers also consider only one ES evaluation
2) ES approaches have been used to evaluate ERPs at different spatial and temporal scales in China. The regional scale and short-term assessments dominated the reviewed papers. A few of them evaluated the impacts of ERPs on ES at multiple spatial scales.
3) The majority of datasets used were obtained from the global and national databases. Proxy models were the most commonly used models to assess the impact of ERPs on ES. However, 40% of the studies did not report model output validation.

Chapter 4 focused on multiple spatial LULC change. The highlights include:

1. The major characteristic of LULC change during the ERPs was a rapid increase of woodland and grassland as well as a rapid decrease of cropland in northern Shaanxi.
2. Large-scale LULC inter-conversion appeared in croplands and grasslands during ERPs period. Croplands were likely converted to grasslands. The cropland and grassland losses and gains occurred in the whole study site.

3. It was found that the annual decrease rates of woodland and grassland in several sub-watersheds during the ERPs period, indicating the ERPs was less successful implementation in these sub-watersheds.

Chapter 5 focused on multiple spatial water-related ES change. The highlights include:

1) Both soil erosion and water yield decreased in the whole study site before and after implementation of the ERPs. However, soil erosion and water yield rapidly decreased in the ERPs period in comparison to pre-ERPs period.
2) Based on watershed analysis, the changes in soil erosion and water yield varied from one sub-watershed to another.

Chapter 6 focused on spatial heterogeneity of relationships between LULC and water-related ES. The highlights include:

1. The ERPs implemented in northern Shaanxi might not always help soil and water conservation, because spatial heterogeneity of relationships among LULC, soil erosion, and water yield existed in the study site.
2. Decreasing of cropland and increasing of grassland have generated the positive impacts on resisting soil erosion. However, increasing of woodland has led to water yield decrease in northern Shaanxi.
3. Trade-offs relationship existed between soil erosion and water yield, which means an improvement in erosion service is achieved at the expense of a decrease in the provision of water in northern Shaanxi.

Chapter 7 focused on how to reduce the negative impacts of the ERPs on water-related ES. The highlights include:

1. Under protection and BAU scenarios, the ERPs are likely to be an important and influential driver on soil erosion and water yield by 2050. Soil erosion values showed a little difference under protection and BAU scenarios, although it decreases in comparison to soil erosion in 2015. However, compared with water yield in 2015, it decreases by 28% (No LULC change scenario), 29% (BAU scenario), and 37% (protection scenario).
2. Water yield under BAU and No LULC change scenarios show relatively small differences, demonstrating that climate factors (e.g. precipitation and ET_0),

ecological restoration and their interactions were likely to place substantial pressures on the provision of water by 2050.

3. Current ecological restoration practices might support soil and water conservation in the future in northern Shaanxi.

8.3 Overall conclusions

In a world of progressive ecosystem degradation, ecological restoration has become ever more important and plays a significant role in sustainable development efforts across China. In turn, the goal of these activities is the provision or improvement of specific sets of ES. By affecting the movement of ecosystem functions, the ERPs connect human activities with the provision of ES. As such, it is a critical component for understanding our influence on ecosystems, and the benefits we receive from them. Increased attention and research on the effects of ERPs on ES provision will ensure that we move towards the creation of better ecosystem management.

My thesis has fulfilled its stated objectives and provided a different perspective to analyse impacts of ERPs on water-related ES which cover the past, present, and reasonably foreseeable future. Our results indicated that the ERPs have different effects on the provision of water-related ES and that these effects can arise both from changes in temporal and spatial scales as well as changes to patterns of climate. Support for this conceptual framework comes from a variety of sources, including our current scientific review (Chapter 2) and modeling exercises (Chapter 3 to 7).

8.4 Future research

There are still several limitations, which offer opportunities for further research.

- How the arrangement of different LULC affect ES?

  As for soil erosion, croplands and grasslands played an important role in controlling soil erosion compared to woodlands. Increasing of woodland had negative impacts on water yield. But, how to manage these LULC to maximum ES benefits remains unclear.

- How the evaluation information gathered in ES assessments could be used to inform decisions?

  One of critical questions related to restoration goal is how to measure and monitor whether the function of the ecosystem is developing towards the desired state. Most of the current studies measuring the success of conducted restoration actions focus on very basic measures. For example, it is well known these ERPs have generated positive impacts on increasing carbon storage and NPP. But they also caused water yield decrease in some regions. These results could prove difficult to estimate whether the ecosystem has changed towards a resilient state. More comprehensive monitoring standards and methods should be developed.

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