Carbon Dynamics in Natural Grasslands in China

A meta-analysis on the relationship between water availability and temperature, and carbon fluxes

BACHELOR THESIS

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Summary

China has acknowledged carbon sequestration as a potential mitigation measure for CO_2 emissions. Government funded research projects found that grasslands are the second largest carbon sink of the country, indicating their potential to capture large amounts of carbon. However, climate change effects, such as water availability extremities and increased temperatures, affect carbon fluxes that determine carbon sequestration. In an attempt to gain a concise overview of carbon fluxes under the threat of global warming, this study attempted to identify the average strength and direction of the relationships between water availability and temperature, and carbon fluxes. Additionally, it acknowledged the spatial variability of water availability and temperature by addressing whether, and how, the studied relationships differ across grassland types.

This study conducted a meta-analysis, including 21 papers which gave 105 regression coefficients as data points. These were used to calculate the average relationships between water availability and GPP, water availability and ecosystem respiration, temperature and GPP and temperature and ecosystem respiration. Additionally, ANOVAs were conducted to identify whether these average relationships differ across grassland types. Key findings from this study have shown that the relationships between water availability and temperature, and carbon fluxes in China grasslands mostly comply with existing knowledge. Overall, positive relationships were identified, and average magnitudes were higher for the relationships between water availability and carbon fluxes, than for the relationships between temperature and carbon fluxes. Surprisingly, the results indicated that grasslands may switch from a carbon sink to a carbon source under conditions of increased water availability. Lastly, differences were found between typical steppes and alpine steppes, with respect to the studied relationships. However, not all differences were significant, and the results were based on few datapoints, limiting this study in some respect.

This study has provided insight into the average relationships between water availability and temperature, and carbon fluxes via the means of a meta-analysis. The findings may contribute to environmental decision-making in China, regarding policy design for carbon sequestration as a mitigation measure for CO_2 emissions.

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1. Introduction

1.1 Background

Globally, increased anthropogenic activities have led to elevated fossil fuel combustion rates. As a result, more carbon is emitted to the atmosphere, inducing climate change (Coumou & Rahmstorf, 2012; Fang, Yu, Liu, Hu & Chapin, 2018; Lal, 2018). Climate change has severe effects, such as temperature increases and more precipitation extremities that range from droughts to severe rainfall pulses (Hu, Yang & Wu, 2003). To defer these consequences, climate scientists have recognized carbon sequestration as an effective mitigation measure (Boot-Handford et al., 2014; Raven & Karley, 2006). Carbon sequestration is the long-term storage of carbon dioxide, and other forms of carbon, in biomass, soils, geologic formations and the oceans. From a terrestrial perspective, the process involves the uptake of carbon from the atmosphere by assimilatory processes in plants (i.e. photosynthesis). Subsequently, the carbon is stored in biomass (Lal, 2008; Raven & Karley, 2006) or transported to the soil where it can remain for an extended period of time in the form of soil organic carbon (SOC) (Beedlow, Tingey, Philips, Hogsett & Olszyk, 2004; Scharlemann, Tanner, Hiederer & Kapos, 2014). Additionally, autotrophs spend their assimilated carbon on respiratory processes, which leads to the release of carbon back into the atmosphere (Lal, 2008; Raven & Karley, 2006).

Over the past fifty years, the Chinese economy has made rapid economic advancements due to industrial developments. These changes have gone hand in hand with increased fossil fuel combustion in China (Fang et al, 2018), which has elevated the carbon footprint of the country. In more recent years, the Chinese government has responded to these issues by acknowledging the importance of carbon sequestration as a measure for the mitigation of CO_2 emissions (Fang et al., 2018). Large-scale projects regarding carbon capture and storage (CCS) have been developed, or are currently in development. These plans are focused on using CCS technologies to remove carbon at the source of industrial carbon emissions (Hao, 2018). However, CCS technologies have been criticised, because the environmental benefits are expected to be insufficient. Additionally, rigorous impact assessments, as well as environmental protection plans need to be developed in order to monitor CCS technologies (Hao, 2018).

In an attempt to gain insight into other instruments for long-term carbon storage, the Chinese government has launched a five year Strategic Priority Project of Carbon Budget with the specific goal of quantifying carbon stocks in terrestrial vegetation, soils and habitats (Fang et al., 2018). Results of the project have confirmed the essential role of forest ecosystems in climate change mitigation due to their potential to store large amounts of carbon in their biomass. In addition to forests, grasslands were found to be the second largest carbon sink in China, storing 32.1% of total terrestrial carbon (compared to 38.9% for forests) (Tang et al., 2017). These results comply with studies emphasizing the key role grasslands have with respect to carbon sequestration as a tool for climate mitigation (Lee, Manning, Rist, Power & Marsh, 2010; Scurlock & Hall, 1998; Soussana et al., 2007).

1.2 Problem statement

In an effort to defer the threat of climate change, the Chinese government has identified grasslands as key ecosystems in the process of carbon sequestration for CO_2 mitigation (Fang et al., 2018). Grasslands are the dominant ecosystem in China, occupying about 40% of the country's total land area (Kang, Han, Zhang & Sun, 2007; Wang et al., 2011) and storing 9-16% of global grassland carbon stocks (Kang et al., 2007). However, these areas vary in terms of land management and regional climate, both of which affect the dynamics between carbon uptake and release (i.e. carbon fluxes) in grasslands (Conant, Paustian & Elliott, 2001; Hu et al., 2003; Lei et al., 2020; Luo, 2007). Land management processes can alter the soil carbon stocks of grasslands, for example by converting native or freely grazed land (i.e. natural grasslands) to croplands or rangelands, or due to the poor management of pastures (Wang et al., 2011). Taking into account that most grassland ecosystems store their assimilated carbon into belowground biomass and the soil (Jones & Donnelly, 2004, Scurlock & Hall, 1998), natural grasslands are likely the biggest contributors to the potential of grasslands for carbon sequestration in China.

In addition to land management, climate change impacts alter the strength of grassland carbon sinks across China. Specifically temperature and water availability are determinants of carbon uptake and release in natural grasslands (Lei et al, 2020; Luo, 2007; Zhang et al., 2014). Due to the size of China, regional climate varieties exist which allow for the existence of different grassland types. Generally, a distinction is made between two major grasslands: typical steppes and alpine steppes (Kang et al., 2007). Considering the climatic diversity among these grassland types (Kang et al., 2007), carbon fluxes determining carbon sequestration are expected to vary across grasslands in China. Therefore, the rate of carbon fluxes in natural grasslands is dependent upon regional climate varieties. An overview with regards to these variations is relevant for the development of effective plans on the management and possible protection of carbon sequestering grasslands.

1.3 Research aim

Many studies that assess carbon fluxes in China on an ecosystem scale do not make a distinction between managed and natural grasslands, nor do they include the effects of temperature and moisture contents. Furthermore, nearly all articles either include ecosystem productivity as an indicator for carbon sequestration, or they assess only carbon influxes or only effluxes (Pan et al., 2017; Wu et al., 2008; Zhu, Johnson, Wang, Ma & Rong, 2015). Due to the relevance of carbon sequestration as a mitigation measure for climate change in China, it is deemed important to take both carbon influxes and carbon effluxes into account. Therefore, this study aims to provide the reader with a concise overview of carbon dynamics in natural grasslands in China by addressing both of them as indicators for carbon sequestration. Additionally, due to the role of carbon sequestration as a potential mitigation measure for climate change, this study takes the effects of climate change on carbon fluxes into account. More specifically, carbon in- and effluxes will be assessed with respect to their relationship with precipitation and temperature. Both precipitation and temperature are linked to carbon fluxes via evapotranspiration (Xiao et al., 2013). Evapotranspiration is the process of water loss from plants and soils, therefore water availability and the temperature in the soil are also relevant. Thus, water availability will indicated by soil moisture and precipitation, and temperature by air and soil temperature. Additionally, a distinction will be made between typical steppes and alpine steppes, since these grassland types are common in China and are different in terms of local climate (Kang et al., 2007). The main objective of this study is to obtain a brief overview of the strength and direction of the relationships between water availability and temperature, and carbon fluxes. Also, attention will be paid to whether these relationships differ across grassland types. To achieve this aim, the following questions will be answered in this thesis by mean of a meta-analysis:

1. What is the direction and strength of the relationship between:

a. Carbon influxes and water availability in natural grasslands in China?
b. Carbon influxes and temperature in natural grassland in China?
c. Carbon effluxes and water availability in natural grassland in China?
d. Carbon effluxes and temperature in natural grassland in China?

2. Do the above-studied relationships between carbon fluxes, and water availability and temperature differ across grassland types in China, and, if so, in what way?

2. Theory

In this chapter the main concepts relevant to this study are explained individually, and with respect to the relationships among them. The concepts of interest are: (1) temperature; (2) water availability; (3) carbon influxes, and; (4) carbon effluxes. The relationships of relevance are: (1) temperature and carbon influxes; (2) temperature and carbon effluxes; (3) water availability and carbon influxes, and; (4) water availability and carbon effluxes. These relationships will be explained irrespective of local variabilities and external factors that may play a role in the magnitude and direction of the relationships of interest. Any deviations from the conceptual model are expected to be due to local or extrinsic variations. If necessary, these will be explained in chapter 5, the discussion.

2.1 Concepts

In research, carbon fluxes can be addressed by a variety of concepts. Subsequently, these concepts are explained according to indicators (i.e. measurements for carbon influxes and carbon effluxes). Net primary productivity (NPP) is a concept that quantifies how much carbon is assimilated by vegetation through photosynthesis, and then stored in biomass (Cao & Woodward, 1998; Zhao & Running, 2010):

(1) $$NPP = GPP - R_a$$

In equation (1) gross primary productivity (GPP) is an indicator for photosynthesis, since both measure carbon fixation in autotrophs (Goulden et al., 2011). The definition of GPP as it is described here complies with the meaning of carbon influxes, therefore GPP is an indicator of carbon influxes in this study. Carbon effluxes describe the loss of carbon from an ecosystem to the atmosphere. R_a indicates the loss of carbon to the atmosphere from autotrophs through respiratory processes. Since some of the carbon assimilated by autotrophs is accumulated in belowground biomass (Scurlock & Hall, 1998), soils also contribute to carbon losses. Additionally, heterotrophs contribute to carbon losses to the atmosphere through respiratory processes (Zhao & Running, 2010). Ecosystem respiration (R_e) is a measurement that encompasses respiration from heterotrophs, autotrophs and soils (Grace, Jose, Meir, Miranda & Montes, 2006). Thus, carbon effluxes are indicated by ecosystem respiration in this study. Overall, the amount of carbon fixed by an ecosystem is indicated by net ecosystem productivity (NEP) (Cao & Woodward, 1998):

(2) $$NEP = GPP - R_e$$

NEP is positive if GPP is higher than ecosystem respiration, which means that an ecosystem is a carbon sink. On the contrary, a negative value for NEP indicates that ecosystem respiration is higher than GPP, and the ecosystem is then a carbon source.

Water availability largely explains variations in carbon fluxes in terms of soil moisture; soil moisture plays a role in the movement of water across soil and leave surfaces (Novick et al, 2016), directly relating to evapotranspiration and thereby carbon dynamics (Willaims & Albertson, 2004) – as will be explained in detail later on (see chapter 2.2). However, oftentimes studies that address the relationship between water availability and carbon fluxes use soil moisture and precipitation interchangeably. The reason for this is the direct effect of precipitation on soil moisture (Wei, Dickinson & Chen, 2008). However, changes in soil moisture content are not solely due to precipitation; snow melt and flood events can play a role as well (Chimner & Welker, 2005). Therefore, this study makes a distinction between precipitation and soil moisture as indicators for water availability Additionally, temperature is related to carbon fluxes (van Dijk, Dolman & Schulze, 2005), and as with moisture content, a distinction is made between air temperature and soil temperature. Both of these measurements affect evapotranspiration from vegetation and soil, thereby contributing to changes in GPP and ecosystem respiration (Niu et al, 2007).

2.2 Identification of Relationships

Relationships between temperature and water availability, and GPP and ecosystem respiration differ in terms of strength and direction. This section will take the direction of the relationships into account. A direction can be either positive or negative, it indicates whether an increase in one of the climate variables leads to an increase or decrease in the respective carbon fluxes.

2.2.1 Relationship between climate indicators and GPP

The relationship between GPP and water availability is twofold. On the one hand, water content within vegetation must be sufficient for the uptake of carbon from the atmosphere (Williams & Albertson, 2004). On the other hand, external (i.e. atmospheric) H_2O concentration needs to be at a certain level to ensure efficient carbon assimilation (Chaves, Flexas & Pinheiro, 2008). In the first case, evapotranspiration is an intermediate factor that regulates carbon assimilatory processes in plants. For carbon to be taken up from the atmosphere stomata have to open, which allows for the diffusion of carbon into the intercellular space, and the loss of H_2O to the atmosphere. Insufficient water content in the stomata inhibits them from opening up, thereby impeding carbon assimilation (Williams & Albertson, 2004). As soil moisture declines, the movement of water to evaporating sites at the soil surface and within the plant is disrupted, inhibiting the plant from opening up its stomata and thereby taking up carbon (Novick et al., 2016). In a second case, a decline in H_2O concentration in the atmosphere reduces the efficiency with which CO_2 can diffuse through the stomata, which leads to decreased carbon uptake by plants (Chaves, Flexas & Pinheiro, 2008; Li et al., 2017). Both of these cases indicate a positive relationship between

GPP and water availability, which means that a rise in precipitation or soil moisture leads to increased GPP.

Air temperature and soil temperature are positively related to GPP. First, under increased temperature conditions the enzyme ribulose-1.5-biphosphate (RuBP) is more abundant in vegetation (Yamori, Hikosaka & Way, 2013). Because this is a critical enzyme for photosynthesis, higher temperatures will result in increased GPP (Sage & Kubien, 2007). However, too high temperatures inhibit GPP, because the assimilatory processes in plants are restricted by plant biochemical processes, which are sensitive to extreme temperatures (Luo, 2007). Second, evapotranspiration is increased by higher temperatures; more moisture will be extracted from soils, as well as from vegetation. At first, induced evapotranspiration due to temperature increases will make the H_2O CO_2 transfer through the stomata happen more efficiently (Williams & Alberston, 2004). However, as temperatures continue to rise, water availability in the soil will decrease (Lakshmi, Jackson & Zehrfuhs, 2003). As a result, evapotranspiration rates decline, as will GPP. Thus, the relationship between temperature and GPP is positive, though constrained by an optimum after which the relationship becomes negative.

2.2.2 Relationship between climate indicators and ecosystem respiration

Unlike GPP, which is mostly mediated by evapotranspiration, ecosystem respiration is dependent on a variety of processes, such as decomposition, growth (Chimner & Welker, 2005) and ecosystem biomass (Yvon-Durocher et al., 2012). Growth and biomass are regulated by GPP, which is positively related to water availability. Both processes result in higher ecosystem respiration rates (Yvon-Durocher et al., 2012), thus as higher water availability increases GPP, more biomass is produced due to growth, which gives rise to higher ecosystem respiration rates. Furthermore, precipitation directly affects soil moisture content (Lakshmi, Jackson & Zehrfuhs, 2003), which facilitates the microbial decomposition of organic matter, resulting in increased ecosystem respiration (Chimner & Walker, 2005; Lei et al, 2020). Additionally, high soil moisture content is associated with plant root and shoot growth, which also leads to higher ecosystem respiration rates (Chimner & Walker, 2005). These processes combined explain the direction of the relationship between ecosystem respiration and water availability as positive.

The relationship of temperature with ecosystem respiration is mediated by decomposition of soil organic matter, as well as growth rates and the amount of biomass in an ecosystem. First, the release of carbon from soils through the decomposition of organic matter is increased under increased soil temperature conditions (Reichstein et al., 2005). Second, growth and biomass as determinants of ecosystem respiration are mediated by GPP; as stated in chapter 2.2.1, higher temperatures increase GPP. This gives rise to a positive relationship between temperature and ecosystem respiration.

2.2.3 Magnitude of the relationships

The magnitude of the relationships between water availability and temperature, and carbon fluxes is due to a variety of factors. These are based on complex interactions between temperature and water availability, and ecosystem respiration and GPP, as introduced in the chapters 2.2.1 and 2.2.2. Because of time constraints I am not able to explain these processes in detail, nor is there time to identify the mechanisms that drive these processes. For this reason, any trends found in the results with respect to the magnitudes of the relationships at hand, will be explained in the discussion (see chapter 5). Rather, this conceptual model aimed to provide the reader with a basic overview of the direction of the relationships between water availability and temperature, and carbon fluxes.

2.3 Grassland Types

In this chapter the distinction between typical steppes and alpine steppes, as the grassland types of interest for this study, will be explained. First, typical steppes, also called temperate steppes, are mostly located in the North and North-East of China, covering most of the province of Inner Mongolia (Kang et al., 2007). Mean annual temperatures (MAT) in this grassland type range from -2 to 5°C, and mean annual precipitation (MAP) is around 250 mm (Fan et al., 2009). Furthermore, within typical steppes a distinction can be made between plant community types, including: *Leymus chinense, Stipa grandis, S. klyrovii, S. bungeana, S. capillata, Artemisia frigida, Agropyron cristatum, Cleistogenes squarrosa, Artemisia intramongolica, A. holoderdron, A. gmelinii, Festuca sulcate, Thymus mongolicus* (Fan et al., 2009; Kang et al, 2007). Alpine steppes are for the most part found across the Tibetan Plateau in China, which ranges from the middle of the country to the South-West where it borders India, Nepal and Bhutan (Kang et al., 2007). The grassland type has MATs that range from -1.3 to -4.1°C and a MAP that ranges from 320 mm in arid regions, to 530 mm in semi-arid regions (Wang, Wang, Li & Cheng, 2007). Alpine steppes host multiple plant communities, such as: *Carex moorcroftii, Stipa purperea, Littledelea racemose, S. subsessiliflora, Festuca kryloviana, Artemisia salsoloide, A. younghusbandi, A. minor*.

3. Methods

In this study a meta-analysis was be performed on the relationships between carbon fluxes, and indicators for temperature and water availability, that are and will be affected by climate change (Hu et al, 2003). A meta-analysis is a quantitative procedure that allows for the combination of numerical data from multiple studies to reach an overarching conclusion on their descriptive statistics, as well as an explanation of potential contrasts between them (Rosenthal & DiMatteo, 2001). The combined results of this analysis were split across two grassland types, namely typical steppes and alpine steppes, to address the spatial distribution of carbon fluxes across different natural grasslands in response to the effects of global warming. The methodology of this study was structured around three basic steps that are taken when conducting a meta-analysis (Rosenthal & DiMatteo, 2001):

1. Defining the dependent and independent variables.
2. Developing a framework for data collection.
3. Describing the statistics for data analysis.

3.1. Dependent and Independent Variables

The dependent and independent variables in this study are based around the main theoretical body introduced by the conceptual framework in chapter 2. Here a distinction between air temperature and soil temperature, and soil moisture and precipitation was introduced. These four variables will be referred to as the partitioned variables, and temperature and water availability will be referred to as the non-partitioned variables (Table 1). Both the partitioned and the non-partitioned variables are unaffected by assimilatory and respiratory processes, therefore they are the independent variables. Consequently, GPP and ecosystem respiration are the dependent variables, because they are expected to be influenced by temperature and water availability, as well as the partitioned variants (i.e. air temperature, soil temperature, precipitation and soil moisture).

Table 1: Overview of the abbreviations used in this study to refer to the relationships examined.

Partitioned relationships		Non-partitioned relationships	
Abbreviation	**Meaning**	**Abbreviation**	**Meaning**
TAxGPP	Air temperature - GPP	TxGPP	Temperature – GPP
TAxER	Air temperature – ecosystem respiration	TxER	Temperature - ecosystem respiration
STxGPP	Soil temperature - GPP	WxGPP	Water availability – GPP
STxER	Soil temperature – ecosystem respiration	WxER	Water availability – ecosystem respiration
PxGPP	Precipitation – GPP		
PxER	Precipitation – ecosystem respiration		
SMxGPP	Soil moisture – GPP		
SMxER	Soil moisture – ecosystem respiration		

3.2. Data Collection

To guide the process of study selection and data collection, a data collection framework was developed. Data collection was guided by the PRISMA framework, which structures the data collection process by distinguishing between four phases: identification, screening, eligibility and inclusion (Moher, Liberati, Tetzlaff & Altman, 2009). To ensure study transparency and replicability, all four stages of the data collection process will be reported on in detail in this chapter. During the identification phase, relevant studies were identified based on the following keywords in Scopus: ‘grassland(s)’, ‘China’ and either ‘precipitation’ or ‘drought’ or ‘temperature’ or ‘soil moisture’ or ‘soil temperature’, and either ‘photosynthesis’ or ‘GPP’ or ‘ecosystem respiration’. Those keywords were used in four separate search strings, which led to a yield of 722 papers which could be used during the screening phase. During this phase the abstract of all articles with relevant titles were read, and all articles that were deemed useful according to their abstract were included in an Excel file (N = 131). Because separate search strings were used during the identification phase N = 26 duplicates were included in the Excel file. After the removal of these duplicates 105 articles remained to be checked for eligibility (third phase). The first layer of criteria to which articles had to comply were (a) location (b) language and (c) is it a natural grassland? The location had to be in China and the grassland had to be natural, meaning that studies considering grazed land or croplands were excluded from this thesis. Furthermore, all articles not in English were not considered as well. This first layer of criteria resulted in 13 articles being removed from this study. A second layer of criteria checked for the usefulness of articles in practical terms, which meant that the studies had to have specific statistics included. I included only the studies that allowed me to calculate regression coefficients (*r*) between independent and dependent variables. To be able to include regression coefficients in this study three types of data were recorded: (1) the correlation coefficient (*r*), (2) the r^2 of linear relationships, or (3) the F-ratio including the sample size (*n*) (Borenstein et al., 2011; Gaertner et al., 2014). If the sample size was not given by the study it was calculated using the degrees of freedom, often provided in the ANOVA table, where $n = df + k$, where k is the number of groups involved in the experiment (i.e. experimental group(s) and control group). Studies were relevant if they quantified the relationship between at least one independent variable and one dependent variable. Regarding the second type of data, if r^2 was provided from linear regression, its square root was taken to determine r. For the third type of data, the F-ratios were used to calculate the correlation coefficient according to equation 2 (Borenstein et al., 2011; Gaertner et al., 2014

(3) $$r = \frac{F^{0,5}}{(n-2-F)^{0,5}}$$

Completion of the second layer of criteria finalized the process of data collection with the inclusion of 21 articles, which yielded a total 105 data points (i.e. regression coefficients). Appendix A, table 4 displays all articles that were included in this study, including details such as grassland type, MAP, MAT and what relationship(s) they included. Based on the location characteristics, and other details provided by the article (e.g. vegetation composition), each site was classified as either a typical steppe, an alpine steppe or grassland type not relevant (see chapter 2.3). The latter indicates that the site characteristics did not match either of the grassland types considered in this study.

3.3. Statistics for Data Analysis

All data was imported from Microsoft Excel to IBM SPSS Statistics 25 (IBM Corp, 2017), which was used for all statistical analyses. First, regression coefficients were transformed into effect size ratios (ESR's) according to Fisher's z-transformation (Borenstein et al., 2011; Gaertner et al., 2014):

(4) $$ESR = \frac{\frac{\ln(1-r)}{\ln(1+r)}}{2}$$

This was a necessary step, since regression coefficients are not continuous measurements, making them unsuitable for calculating descriptive statistics, such as mean effect sizes and the variance. Furthermore, the ESR can be used to interpret the strength and direction of a relationship; in the case of no relationship, r = ESR = 0. ESRs have a different range than *r*, namely -2,6467 to 2,6467, thus |2,6467| is indicative of a strong relationship compliant with r = |1|. As with the regression coefficient, the negative sign in the ESR indicates a decreasing effect of the independent variable on the dependent variable. On the contrary, a positive ESR illustrates a relationship where the independent variable increases in the dependent variable. However, these statements on decreasing and increasing effects only apply if causation is supported with supplementary literature. Before any statistical tests were ran, boxplots were created for each partitioned relationship to check for outliers in the data (Appendix B). Identified outliers were traced back to their source article to assess the circumstances under which the relationship was determined. If abnormalities in the experimental set-up were identified (e.g. severe weather events), the outlier was removed from the dataset in SPSS and thereby not included in data analyses.

Because the ESRs included in my data file were based on the partitioned relationships only, four new variables had to be computed to represent the non-partitioned variables. First, the variable TxGPP was computed by merging the variables TAxGPP and STxGPP into one, then the variable TxER was computed by combining the variables TAxER and STxER. Furthermore, for water availability, the variable WxGPP was computed by merging the variables PxGPP and SMxGPP into one. Last, WxER was created by combining the variables PxER and SMxER (Table 1). For each relationship (partitioned and non-partitioned) the mean ESR was computed. Additionally, the significance of the mean ESRs was tested using confidence intervals of 95%, according to the following formula:

(5) $$m - 1.96\frac{\sigma}{\sqrt{n}} < \mu < m + 1.96\frac{\sigma}{\sqrt{n}}$$

Where σ is the standard deviation of the population, *m* is the mean ESR and μ is the population mean. The confidence interval provides a range for values of μ that are statistically significant at α = 0,05. If 0 does not fall into this range, the mean ESR is significant (i.e. significantly different from 0).

One-way Analyses of Variances (ANOVAs) were performed with the partitioned relationships as dependent variables and the grassland types (i.e. typical steppes and alpine steppes), as the group variables. The test statistics from the ANOVAs, in combination with their significance level, were used to determine whether the average strength and direction of the relationships differed significantly among the grassland types. It yields the F statistic, accompanied by a significance level. If this significance level is lower than 0.05, there are significant differences between typical steppes and alpine steppes regarding the relationship it was calculated for. Because ANOVAs assume homogeneity of variance Levene’s test was conducted beforehand to assess equality of variances between groups (see Appendix C). It tests the null hypothesis that the compared groups have equal variances, therefore an outcome of $p < 0.05$ indicates heterogeneity of variance. In the case of a violation of this assumption (i.e. $p < 0.05$) the one-way ANOVA was deemed unsuitable for testing, and therefore replaced by the more robust Brown-Forsythe test. Results from this test yield the same test statistic (i.e. F), accompanied by a significance level, which can be interpreted the same as an ANOVA.

4. Results

4.1 Climate data

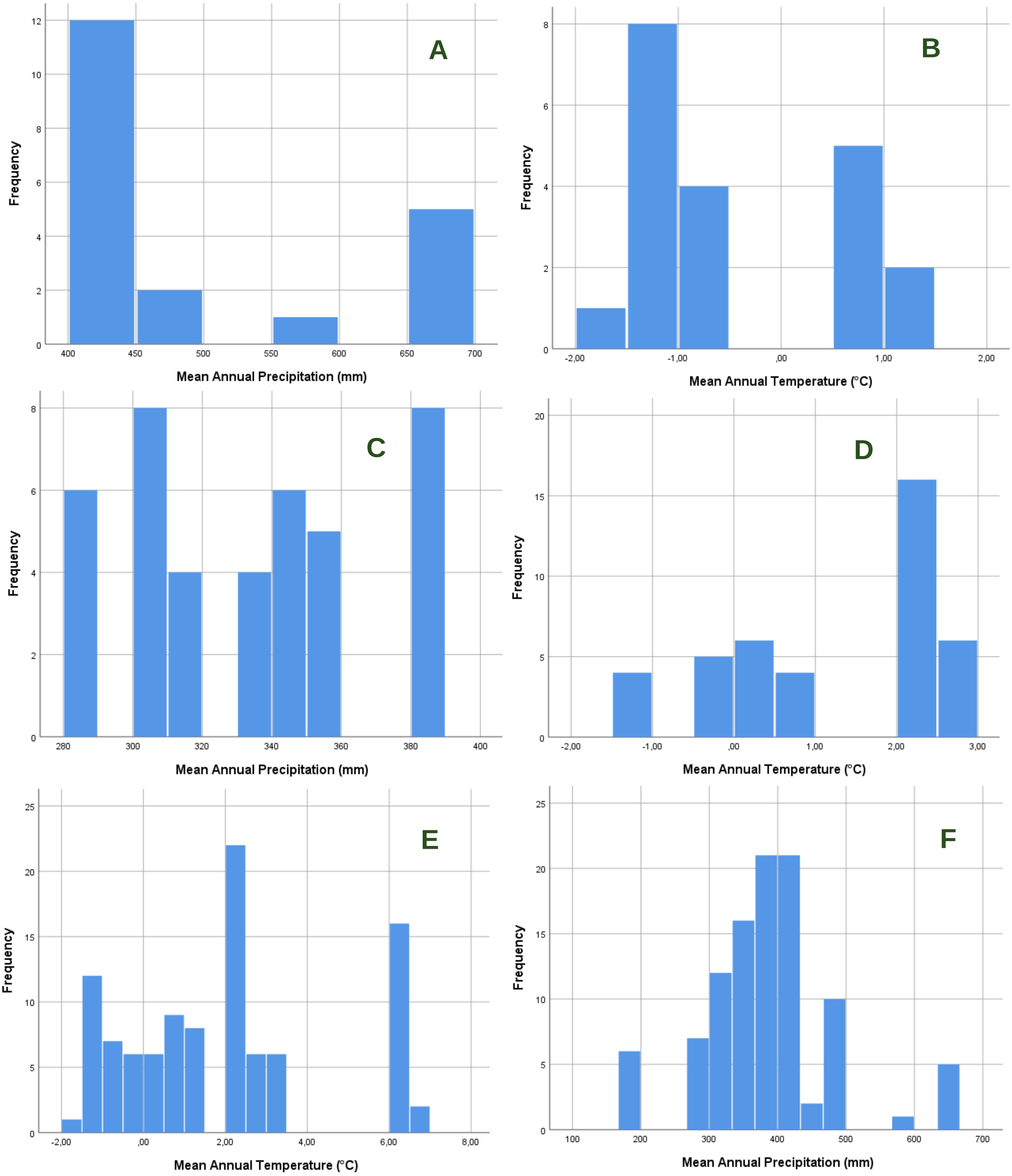

Figure 1: Histograms of the frequency of (a) MAP in alpine steppes, (b) MAT in alpine steppes, (c) MAP in typical steppes, (d) MAT in typical steppes, (e) MAP in all grasslands, and (f) MAT in all grasslands.

Figure 1 presents climate data from the study sites used in this meta-analysis. The overview presents the differences between typical steppes and alpine steppes. MAP is higher in alpine steppes than in typical steppes, in the former it measures predominantly 400 mm/year or higher, whereas in the latter it is more evenly distributed with a range of 280-380 mm/year. With respect to MAT, observations are higher in typical steppes when compared to alpine steppes. Overall, MATs are concentrated around 1-1.5°C, with some outliers around 2-3°C and again around 6°C. Furthermore, overall MAP is shaped like a bell-curve, with its peak around 400 mm. However, most observations were made in the area MAP <400 mm, rather than MAP >400 mm.

4.2 Outliers

Boxplots revealed five outliers in the data: one in the variable describing the ESRs of the relationship between precipitation and GPP (Appendix A, Figure 9), two in the variable describing the relationship between precipitation and ecosystem respiration (Appendix A, Figure 10), and two in the variable regarding the relationship between soil moisture and GPP (Appendix A, Figure 11). Table 2 describes their values and whether they were removed or not.

Table 2: Overview of all observed outliers and whether they were removed, based on the boxplots in Appendix A.

Study	Case	Relationship	ESR	Removed?
Li et al., 2016	62	PxGPP	-2.64665	Yes
Niu et al., 2007	85	PxER	1.94591	No
Fang et al., 2018	26	PxER	0.213171	No
Wang et al., 2008	86	SMxGPP	-1.33308	No
Fu et al., 2009	27	SMxGPP	-1.47222	Yes

Case 62 was removed from the dataset because the independent variable was the effect of drought, rather than precipitation (Li et al., 2016). This led to the unjust addition of a strong negative ESR, while the general relationship observed between precipitation and GPP is positive. Furthermore, case 27 regarding the relationship between soil moisture and GPP was removed from the dataset. The study from which the observation was obtained, noticed a significant suppression of GPP due to less precipitation and soil moisture in one of the two observational years (Fu et al., 2009). Such extremities were sufficient ground for the removal of the observation from the data set.

4.3 Mean ESRs

To describe the average strength and direction for each relationship, partitioned and non-partitioned, mean ESRs were computed (see Appendix C). Figure 2 displays the mean ESR's for the non-partitioned variables, including confidence intervals represented as error bars.

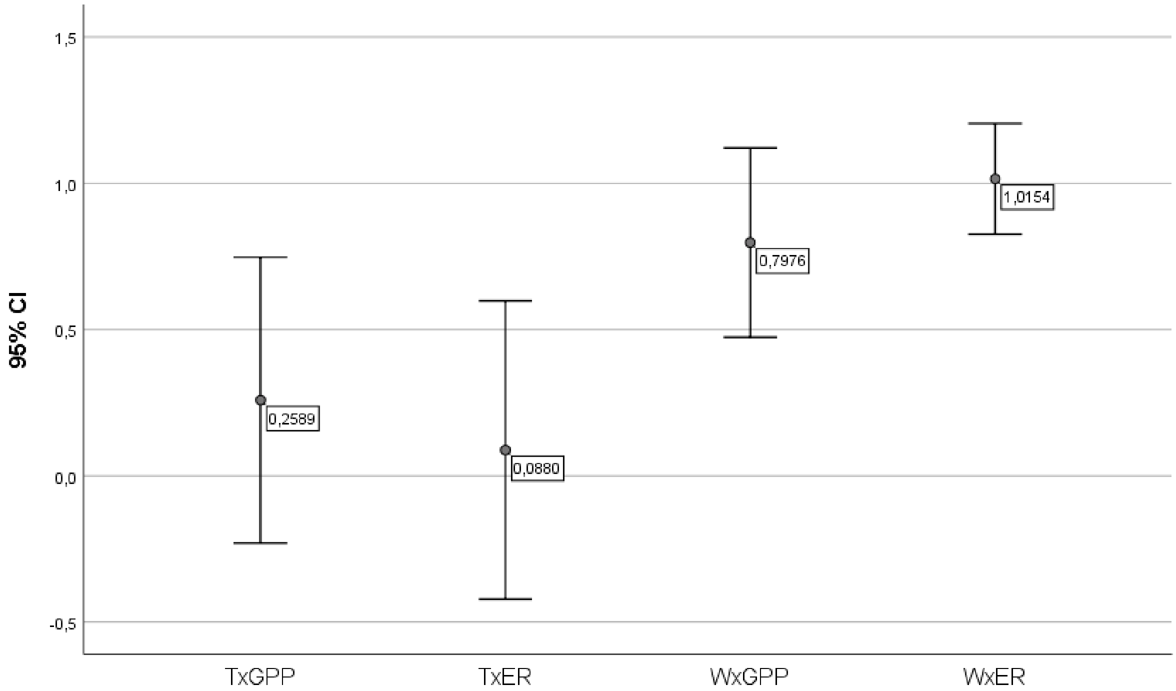

Figure 2: Mean ESRs and confidence intervals for the non-partitioned variables. The dots represent the mean for each data point, including its value in the box. The errors bars represent the confidence intervals at 95%.

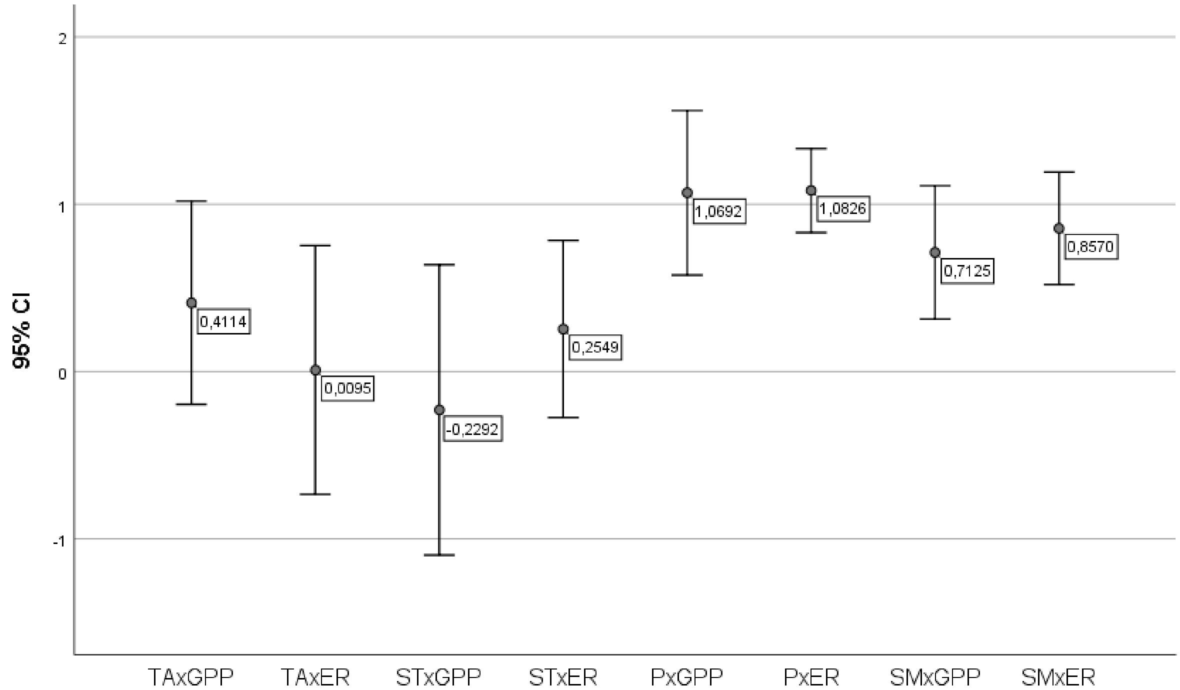

Figure 3: Mean ESRs and confidence intervals for the partitioned variables. The dots represent the mean for each data point, including its value in the box. The errors bars represent the confidence intervals at 95%.

The findings in Figure 2 present that all of the average relationships between the non-partitioned independent variables, and carbon fluxes are positive. This is also observed with the partitioned relationships in Figure 3, however the average direction of the relationship between soil temperature and GPP is an exception, since it has a negative mean ESR of m = -0.2292. This means that a negative relationship exists between soil temperature and GPP. Considering the non-partitioned average relationships (Figure 2), the relationships between water availability and temperature, and carbon fluxes are not all of the same magnitude: the mean ESRs of WxGPP (m = 0.7977) and WxER (1.0154) are higher than the mean ESRs of TxGPP (m = 0.2589) and TxER (m = 0.0880). Thus, water availability has stronger relationships with carbon fluxes than temperature does. This is also observed in Figure 3, where the mean ESRs for the partitioned relationships are visualized; relationships between indicators for water availability and carbon fluxes have higher mean ESRs compared to relationships between water-related variables and carbon fluxes. The observation that all of the average relationships between temperature, and indicators for temperature, and carbon fluxes are insignificant at $\alpha = 5\%$ stand out. Especially because, on the contrary, the relationships between water availability, and its indicators, and carbon fluxes are all significant at $\alpha = 5\%$. (Figure 2; Figure 3).

Furthermore, while temperature is more strongly correlated with GPP, water availability has a stronger relationship with ecosystem respiration (Figure 2). This observation does not hold up for the partitioned relationships between indicators for temperature and carbon fluxes. While air temperature has a stronger correlation with GPP than with ecosystem respiration, the reverse is true for soil temperature, which is more strongly related to ecosystem respiration than to GPP (Figure 3). Considering the partitioned relationships with water availability as an independent variable, the observation that ecosystem respiration is more strongly correlated with changes in water availability than GPP still stands (Figure 3). Moreover regarding indicators of water availability, precipitation has a stronger relationship with carbon fluxes than soil moisture does. Increases in precipitation are more strongly related to higher GPP and ecosystem respiration than increases in soil moisture are (Figure 3).

4.4 Differences Between Typical Steppes and Alpine Steppes

4.4.1 Mean ESRs

The mean ESRs and confidence intervals (95%) of the relationships between the independent, partitioned variables and the dependent variables were computed for typical steppes and alpine steppes, respectively (Figure 4). ANOVAs were conducted to assess whether the differences of the average ESRs between the two grassland types were significantly different from each other (Table 3).

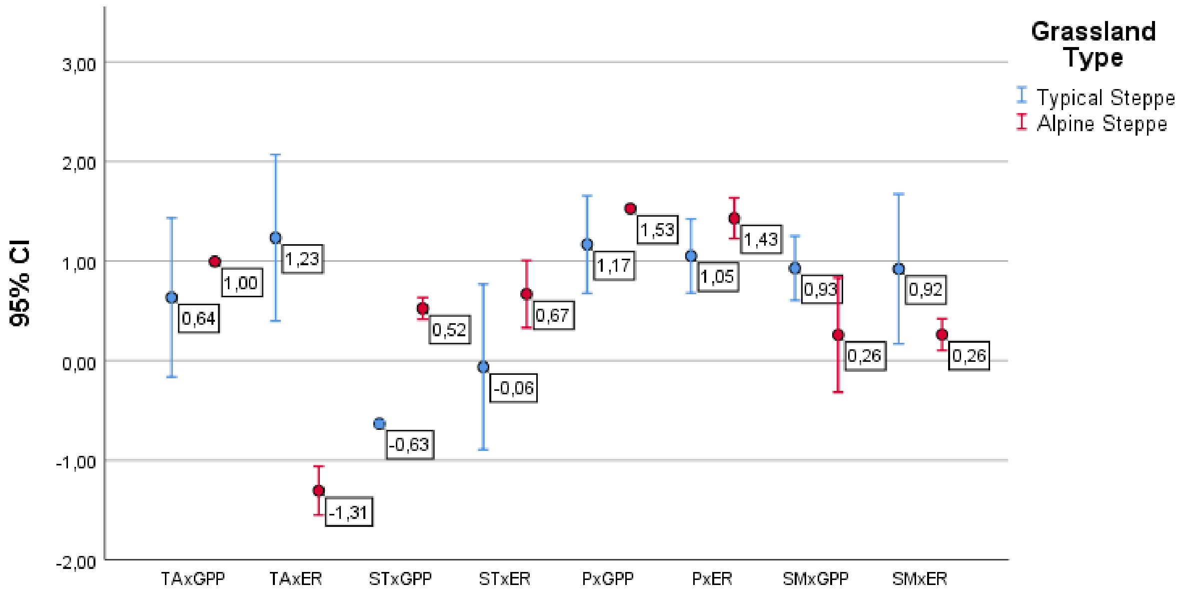

Figure 4: Mean ESRs and confidence intervals for the partitioned variables. A distinction is made between typical steppes and alpine steppes. The dots represent the mean for each data point, including its value in the box. The errors bars represent the confidence intervals at 95%.

Figure 4 presents the mean ESRs of the two grassland types for each partitioned relationship. Firstly, relating to indicators for water availability: the magnitude of the relationship between precipitation and carbon fluxes is higher in alpine steppes than in typical steppes. On the contrary, soil moisture is more strongly related to carbon fluxes in typical steppes than in alpine steppes. However, while differences in means are observed with respect to the grassland types, of the contrasts described above the only significant difference found was for the relationship between soil moisture and ecosystem respiration.

More extreme differences are observed on the left-hand side of the figure, which visualizes the average relationships between temperature indicators and carbon fluxes. The most extreme difference is observed in the mean ESR for the average relationship between air temperature and ecosystem respiration: m = 1.23 and m = -1.31 for typical steppes and alpine steppes, respectively. This indicates that a positive relationship between air temperature and ecosystem respiration exists in typical steppes, whereas that same relationship is negative in alpine steppes. The same observation is true for the mean ESRs regarding the relationship between soil temperature and GPP. Whereas the mean ESR is positive for alpine steppes (m = 0.52), it is negative for typical steppes (m = -0.63).

4.4.2 Analyses of Variance

To test whether the observed differences between the grassland types are significant, ANOVAs were conducted.

Table 3: Test results of the analyses of variance (via ANOVA or Brown-Forsythe). Significant results are in bold.

Relationship	df	F	Significance
TAxGPP	1	1.04	0.758
TAxER	1	16.535	**0.015**
STxGPP	1	458.319	**0.019**
STxER	1	3.452	0.122
PxGPP	1	0.260	0.622
PxER	1	0.967	0.354
SMxGPP	1	4.851	0.055
SMxER	1	32.906	**0.011**

Significant numbers in Table 3 represent significant differences between the mean ESRs of typical steppes and alpine steppes with respect to the relationship at hand. The most extreme differences observed, as described in the paragraph above (TAxER and STxGPP) are significant ($F(1) = 16.535$, $p = 0.015$ and $F(1) = 458.319$, $p = 0.019$, respectively). Furthermore, there is a significant difference between the averages for the relationship between soil moisture and ecosystem respiration in typical steppes and alpine steppes ($F(1) = 32.906$, $p = 0.11$).

6. Discussion

6.1 Interpretation of Results

6.1.1 Grasslands Overall

The significant results obtained in this study are compliant with existing knowledge on the relationships between temperature and water availability, and carbon fluxes. First, all average relationships, but one (STxGPP), have a positive direction (Figure 3; Figure 4). This is in accordance with the theory section (see chapter 2), which explains that increases in precipitation and soil moisture lead to higher rates of GPP and ecosystem respiration. Second, the magnitude of the positive relationships is observed to be larger for the relationships with water availability as an independent variable, than for those with temperature as an independent variable. This is not unexpected, since the theory states that water availability is the primary driver of carbon fluxes, when compared to temperature (Chimnes & Welker, 2005; Novick et al., 2016; Williams & Albertson, 2004).

With respect to the insignificant results, all temperature-related relationships were found to be insignificant (Figure 2; Figure 3), which indicates that no relationship between indicators for temperature and carbon fluxes is present at all. However, it is likely that the insignificance of these average relationships is due to the presence of a third variable, namely solar radiation. Solar radiation is a dominant explanatory variable for changes in carbon fluxes over temperature. Irradiance from the sun increases photosynthesis and thus GPP, as a consequence ecosystem respiration rates rise due to metabolic processes and growth (van Dijk, Dolman & Schulze, 2005). Because solar radiation and temperature can co-occur, it is possible that the – though insignificant – relationships between indicators for temperature and carbon fluxes are mediated by irradiance from the Sun.

Furthermore, ecosystem respiration appears to be slightly more strongly related to water availability than GPP (Figure 3). A reason for this observation might be that most carbon in grasslands is stored in its soils as SOC. Soil microorganisms partially regulate ecosystem respiration from this SOC via decomposition. It was found that a high variability of precipitation, which is related to soil moisture, leads to a high turnover of microbial biomass with increased carbon loss as a consequence (Yan, Marschner, Cao, Zuo & Qin, 2015). However, this does not imply that the stronger relationship between water availability and ecosystem respiration is caused by the sensitivity of soil microorganisms to soil moisture. Though, this factor might play a role in the realisation of this correlation.

Lastly, within the indicators for water availability, differences were observed regarding the magnitudes of their relationships with carbon fluxes. It was found that, precipitation is more strongly related to carbon fluxes than soil moisture is. This observation can be a consequence of the presence of an interaction effect between soil moisture and temperature, In this case, higher temperatures lead to more evapotranspiration from the soil, which impedes soil moisture and thereby its relationship with carbon fluxes. As a consequence, some of the variability in carbon fluxes due to soil moisture might be explained by high soil and air temperature. Additionally, the relationship between precipitation and carbon fluxes is regulated through a variety of factors, such as overall precipitation, the heaviness of a pulse and the frequency of precipitation pulses (Huxman et al., 2004). Since no clear distinction was made between precipitation frequency, and pulse size or overall precipitation in this study, the magnitude of the correlation between precipitation and carbon fluxes can be mediated by the inclusion of these concepts in the dataset. Correlations between these factors combined and carbon fluxes may be higher than correlations between overall precipitation and carbon fluxes alone.

6.1.2 Typical Steppes vs Alpine Steppes

A significant difference between typical steppes and alpine steppes was found for the relationship between soil moisture and ecosystem respiration. In this case, the magnitude of the average relationship was higher for typical steppes than for alpine steppes. Ecosystem respiration becomes more sensitive to variations in soil moisture as drought becomes a more prominent factor in an ecosystem (Merbold et al., 2009). Since typical steppes are drier than alpine steppes (Figure 1), it is not unexpected that this difference was observed. However, drought-prone ecosystems are identified as sites that receive less than 1000 mm of precipitation per year (Merbold et al., 2009), which would include both typical steppes and alpine steppes. Nonetheless, since typical steppes receive less precipitation on a yearly basis compared to alpine steppes, they are more sensitive to water availability (i.e. their ESR is of a higher magnitude).

Significant differences were found between the grassland types with respect to the relationships between air temperature and ecosystem respiration, and soil temperature and GPP. In the case of the relationship between air temperature and ecosystem respiration, a positive mean ESR was found for typical steppes and a negative mean ESR was found for alpine steppes. The result for alpine steppes is based on two samples which have been obtained from the same study (Zhao et al., 2019a). This study based its results off of experiments in which each warming plot also experienced increased precipitation. Usually, higher temperatures offset decreases in soil moisture, which leads to decreased GPP. Because GPP is positively related to ecosystem respiration (Chimner & Welker, 2005), respiratory processes will also experience decreases (Yvon-Durocher et al., 2012). However, Zhao and his colleagues (2019a) experienced increased precipitation over the warming plots, therefore the expected effect of warming on moisture content was not observed, leading to the negative relationship between ecosystem respiration and air temperature as observed in this study.

Furthermore, significant differences were found between typical and alpine steppes with respect to the relationship between soil moisture and GPP. The relationship was negative for typical steppes, but positive for alpine steppes. It is expected, that this contrasting observation is due to the small amount of data points (i.e. two) on which each observation is based. Additionally, the finding is based on just two articles, one for each grassland type. Despite that, no reasons for the contradictory results were found within the studies itself. Therefore, the result might be a consequence of a yet to be explained mechanism.

6.3 Limitations

Despite the insightful results that have been obtained from this research, the findings of the meta-analysis are based on a small sample size (n = 21), which has limited this research in some respects. Though, one could interpret the amount of data points as ample (there are 105), many are retrieved from the same study. In essence, there are a few powerful studies in this meta-analysis that possibly dominate the results. Additionally, because there were many relationships to be dissected in this study, the amount of data points on which some results are based is insufficient. This was especially limiting to the interpretation of the results regarding the significant differences between typical steppes and alpine steppes. Despite this limitation, interesting results were retrieved from this section of the study. The most evident reason for insufficient sample sizes in this study is that not enough data is available; of 722 hits on Scopus only 21 articles were useful to this meta-analysis. To gain a complete insight in the relationship between climate change effects and carbon fluxes in China grasslands, further research should focus predominantly on doing, and reporting on, field measurements. Additionally, more research is required on the differences in carbon fluxes among grassland types, especially with respect to local climate varieties.

This research was also limited because it did not take any temporal scales into account. Therefore the concepts of precipitation and temperature were vaguely defined in the theoretical background of this meta-analysis. No strict guidelines were designed when it came to distinguishing between precipitation and precipitation pulses, and between temperature and the duration of an extreme temperature event. However, the duration and the magnitude of a precipitation event do matter for the direction and strength of carbon fluxes (Huxman et al., 2004; Li et al., 2019). Additionally, heat waves should be taken into account when temperature is a variable of interest (Yuan et al., 2015). Thus, it is recommended that future research on the relationship between water availability and carbon fluxes, makes distinctions between overall precipitation, the frequency of precipitation pulses and the heaviness of a pulse. Additionally, future research should differentiate between temperature and heat waves, when carbon sequestration is assessed.

6.3 Contribution to Research

The results of this thesis have presented an overview of the relationships between water availability and temperature, and carbon fluxes in China grasslands, as it is currently understood in sustainability science. The findings have indicated that carbon fluxes are most strongly related to water availability. Additionally, ecosystem respiration has a higher correlation with water availability than GPP does. These findings are relevant to environmental policymakers in China, because they provide insights into the performance of grasslands as carbon sinks (or sources) under the threat of global warming.

For this study, water availability is the most relevant climate factor, because correlations between indicators for temperature and carbon fluxes were insignificant. It is expected that while precipitation will decrease in north-eastern China (i.e. typical steppes), western (i.e. alpine steppes) and south-eastern China will experience higher precipitation rates (Piao et al., 2010; Shi et al., 2007). With respect to the positive relationship between precipitation and carbon fluxes identified in this study, supported by supplementary literature (see chapter 6.1.1), some predictions can be made – though with caution. First, decreased rates of GPP and ecosystem respiration may be observed in north-eastern China as a result of less precipitation due to climate change. Second, on the contrary, increases in carbon fluxes in western and south-eastern China might occur in the future because of higher precipitation in these regions. Despite conflicting predictions and observations regarding water availability in China, the whole country will be experiencing higher temperatures (Piao et al., 2010). Higher temperatures lead to increased evapotranspiration, which has a negative effect on soil moisture content (Piao et al., 2010). Considering the observed positive relationship between soil moisture and carbon fluxes, supported by existing literature (see chapter 6.1.1), global warming may lead to reduced rates of GPP and ecosystem respiration in grasslands in China.

These findings contribute to the discussion of carbon sequestration measures in China. As the introduction presented, China is developing CCS technologies to capture carbon at industrial sources (Hao, 2018), while simultaneously researching how a variety of biomes might contribute to the mitigation of CO_2 emissions (Fang et al., 2018). Placing the observed relationships between water availability and temperature, and carbon fluxes into the context of (future) climate change in China, can contribute to environmental decision-making regarding carbon sequestration instruments in the country. Additionally, this thesis has created a basis for further research on variations in carbon fluxes across grassland types in

China. As supplementary literature has introduced, local climate variabilities exist in the country (Piao et al., 2010; Shi et al., 2007), indicating that not all grasslands are expected to have the same response to global warming.

7. Conclusion

In conclusion, water availability and temperature are both positively correlated with ecosystem respiration and GPP. These findings comply with the existing literature, namely that increased precipitation and temperature lead to higher rates of assimilatory processes (i.e. GPP) and respiratory processes. Additionally, it was found that indicators for water availability are more strongly related to carbon fluxes than indicators for temperature in China’s grasslands. These results were in line with current theory as well. No significant relationships between temperature and carbon fluxes in grasslands in China were identified, which was unexpected. Despite possible explanations introduced in the discussion, such as the presence of solar radiation as a mediating variable, further research should dissect the relationship between temperature and carbon fluxes more thoroughly.

The relationships between indicators for temperature and precipitation, and carbon fluxes were also assessed for typical steppes and alpine steppes, as well as the differences between them. The results found for these assessments were conflicting, and they remain largely unexplained due to the lack of existing literature. No clear pattern could be identified from the results, nor was there sufficient literature to support individual findings. Despite that, significant results were obtained and future research should thus continue to explore if, and how, carbon fluxes vary across grassland types.

Overall, this study has gained useful insights in the relationships between climate change effects and carbon fluxes in China´s grasslands. Nonetheless, from the findings of this study no predictions can be made regarding the overall effect of global warming on the carbon sequestration potential of China´s grasslands. This is a consequence of the absence of a significant average relationship between temperature and carbon fluxes. Still, it is expected that the results can serve as a basis for future research on carbon sequestration in grasslands. Additionally, they might contribute to environmental decision-making in China. Especially with respect to the trade-off between CCS technologies that work at the source of the emissions, and carbon storage in grasslands.

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9. Appendix

A. Results from data collection

Table 4: Dataset used for the statistical analyses in this thesis, a result from the data collection process as explained in chapter 3.2.

Case	Source	Grassland type	MAT	MAP	ESR	Measurement
1	Li et al. (2019)	Typical Steppe	2.5	281	0.996215	P x GPP
2		Typical Steppe	2.5	281	0.590145	P x GPP
3		Typical Steppe	2.5	281	0.867301	P x GPP
4		Typical Steppe	2.5	281	1.020328	P x GPP
5		Typical Steppe	2.5	281	0.618381	P x GPP
6		Typical Steppe	2.5	281	0.996215	P x GPP
7	Zhao et al. (2019)	Typical Steppe	2.13	303	0.792814	TA x GPP
8		Typical Steppe	2.13	303	1.33308	P x GPP
9		Typical Steppe	2.13	303	1.156817	P x GPP
10		Typical Steppe	2.13	303	1.293345	SM x GPP
11		Typical Steppe	2.13	303	1.33308	TA x ER
12		Typical Steppe	2.13	303	1.127029	P x ER
13		Typical Steppe	2.13	303	1.020328	P x ER
14		Typical Steppe	2.13	303	1.33308	SM x ER
15		Not relevant	6.06	384	-1.65839	TA x GPP
16		Not relevant	6.06	384	1.831781	P x GPP
17		Not relevant	6.06	384	1.589027	P x GPP
18		Not relevant	6.06	384	2.092296	SM x GPP
19		Not relevant	6.06	384	-0.79281	TA x ER
20		Not relevant	6.06	384	1.188136	P x ER
21		Not relevant	6.06	384	1.156817	P x ER
22		Not relevant	6.06	384	1.071432	SWC x ER
23	Fang et al. (2018)	Typical Steppe	0.9	338	0.53606	TA x GPP
24		Typical Steppe	0.9	338	2.29756	TA x ER
25		Typical Steppe	0.9	338	0.13074	P x GPP
26		Typical Steppe	0.9	338	0.213171	P x ER
27	Fu et al. (2009)	Not relevant	-	-	-1.47222	SM x GPP
28		Not relevant	-	-	0.928727	SM x ER
29		Not relevant	-	-	-0.79281	P x GPP
30		Not relevant	-	-	0.56273	P x ER
31	Fu et al. (2006)	Typical Steppe	-1.1	313	0.725005	TA x GPP
32		Typical Steppe	-1.1	313	0.57634	TA x GPP
33		Typical Steppe	-1.1	313	0.331647	SM x GPP
34		Typical Steppe	-1.1	313	0.693147	SM x GPP
35	Hu et al. (2018)	Typical Steppe	-0.4	350	1.127029	SM x GPP
36	Fu et al. (2018)	Alpine Steppe	1.3	476.8	1.527524	P x GPP
37		Alpine Steppe	1.3	476.8	0.928727	SM x GPP
38	Chen et al. (2016)	Not relevant	1.34	408.45	1.375768	TA x GPP

39		Not relevant	1.34	408.45	1.293345	TA x GPP
40		Not relevant	1.34	408.45	1.375768	TA x GPP
41		Not relevant	1.34	408.45	0.57634	TA x ER
42		Not relevant	1.34	408.45	1.098612	TA x ER
43		Not relevant	1.34	408.45	0.244774	TA x ER
44	Guo et al. (2015)	Typical Steppe	-0.4	350	0.950479	P x GPP
45		Alpine Steppe	-2	580	0.996215	TA x GPP
46	Yang et al. (2013)	Not relevant	3.2	183.9	1.045371	SM x GPP
47		Not relevant	3.2	183.9	1.65839	SM x GPP
48		Not relevant	3.2	183.9	1.127029	SM x GPP
49		Not relevant	3.2	183.9	1.156817	SM x ER
50		Not relevant	3.2	183.9	1.738049	SM x ER
51		Not relevant	3.2	183.9	1.256153	SM x ER
52	Zhao et al. (2019a)	Alpine Steppe	3.2	415	-1.18814	TA x ER
53		Alpine Steppe	-0.6	415	1.33308	P x ER
54		Alpine Steppe	-0.6	415	-1.42193	TA x ER
55		Alpine Steppe	-0.6	415	1.527524	P x ER
56	Zhao et al. (2019b)	Alpine Steppe	-0.6	414.6	-2.64665	TA x ER
57		Alpine Steppe	-0.6	414.6	-2.0923	TA x ER
58		Alpine Steppe	-0.6	414.6	-2.0923	TA x ER
59	Bao et al. (2019)	Not relevant	6.9	448	0.30952	P x GPP
60		Not relevant	6.9	448	0.972955	P x ER
61	Li et al. (2016)	Typical Steppe	-0.48	358	-1.29334	TA x GPP
62		Typical Steppe	-0.48	358	-2.64665	P x GPP
63		Typical Steppe	-0.48	358	0.758174	ST x ER
64		Typical Steppe	-0.48	358	1.293345	SM x ER
65	Luan et al. (2016)	Alpine Steppe	0.9	656.8	-0.37689	SM x GPP
66		Alpine Steppe	0.9	656.8	-0.4118	SM x GPP
67		Alpine Steppe	0.9	656.8	0.40006	SM x ER
68		Alpine Steppe	0.9	656.8	1.045371	ST x ER
69		Alpine Steppe	0.9	656.8	0.829114	ST x ER
70	Ganjurjav et al. (2015)	Alpine Steppe	-1.2	431.7	0.57634	ST x GPP
71		Alpine Steppe	-1.2	431.7	0.472231	ST x GPP
72		Alpine Steppe	-1.2	431.7	0.376886	ST x ER
73		Alpine Steppe	-1.2	431.7	0.423649	ST x ER
74		Alpine Steppe	-1.2	431.7	0.56273	SM x GPP
75		Alpine Steppe	-1.2	431.7	0.590145	SM x GPP
76		Alpine Steppe	-1.2	431.7	0.244774	SM x ER
77		Alpine Steppe	-1.2	431.7	0.140926	SM x ER
78	Niu et al. (2007)	Typical Steppe	2.1	385.5	2.29756	TA x GPP
79		Typical Steppe	2.1	385.5	0.810743	TA x GPP
80		Typical Steppe	2.1	385.5	0.996215	TA x ER
81		Typical Steppe	2.1	385.5	0.30952	TA x ER
82		Typical Steppe	2.1	385.5	1.831781	P x GPP
83		Typical Steppe	2.1	385.5	2.646652	P x GPP
84		Typical Steppe	2.1	385.5	1.472219	P x ER

85		Typical Steppe	2.1	385.5	1.94591	P x ER
86	Wang et al. (2008)	Not relevant	2	290	-1.33308	SM x GPP
87	Tian et al. (2015)	Typical Steppe	0.3	340	-0.61838	ST x GPP
88		Typical Steppe	0.3	340	-0.64752	ST x GPP
89		Typical Steppe	0.3	340	-0.42365	ST x ER
90		Typical Steppe	0.3	340	-0.52298	ST x ER
91		Typical Steppe	0.3	340	0.792814	SM x GPP
92		Typical Steppe	0.3	340	0.549306	SM x ER
93	Jiang et al. (2012)	Not relevant	6.4	471	0.677666	TA x GPP
94		Not relevant	6.4	471	-1.12703	TA x GPP
95		Not relevant	6.4	471	0.497311	TA x GPP
96		Not relevant	6.4	471	-1.29334	TA x GPP
97		Not relevant	6.4	471	0.40006	TA x ER
98		Not relevant	6.4	471	0.758174	TA x ER
99		Not relevant	6.4	471	1.589027	TA x ER
100		Not relevant	6.4	471	0.792814	TA x ER
101	Xia et al. (2009)	Typical Steppe	2.1	383	-0.92873	ST x GPP
102		Typical Steppe	2.1	383	-0.44769	ST x ER
103		Typical Steppe	2.1	383	0.887184	SM x GPP
104		Typical Steppe	2.1	383	0.4847	SM x GPP
105		Typical Steppe	2.1	383	0.647523	SM x ER

B. Determination of outliers: boxplots

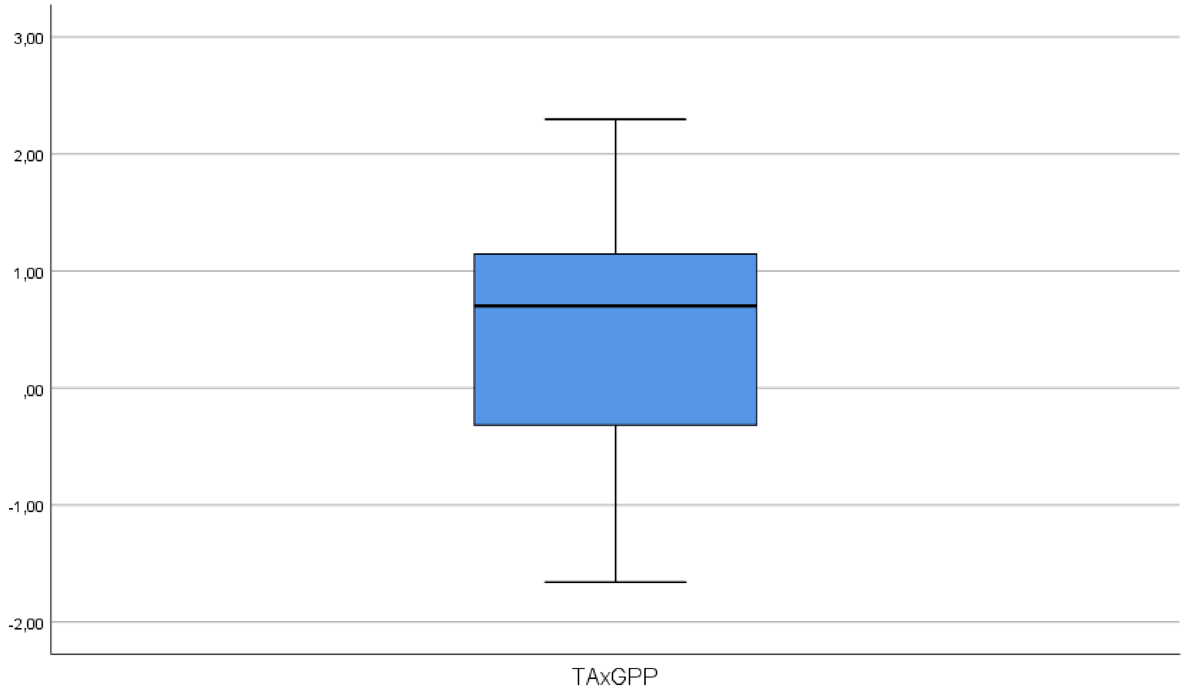

Figure 5: Boxplot of the relationship between air temperature and GPP. Outliers are indicated with a dot separate from the box and the whiskers.

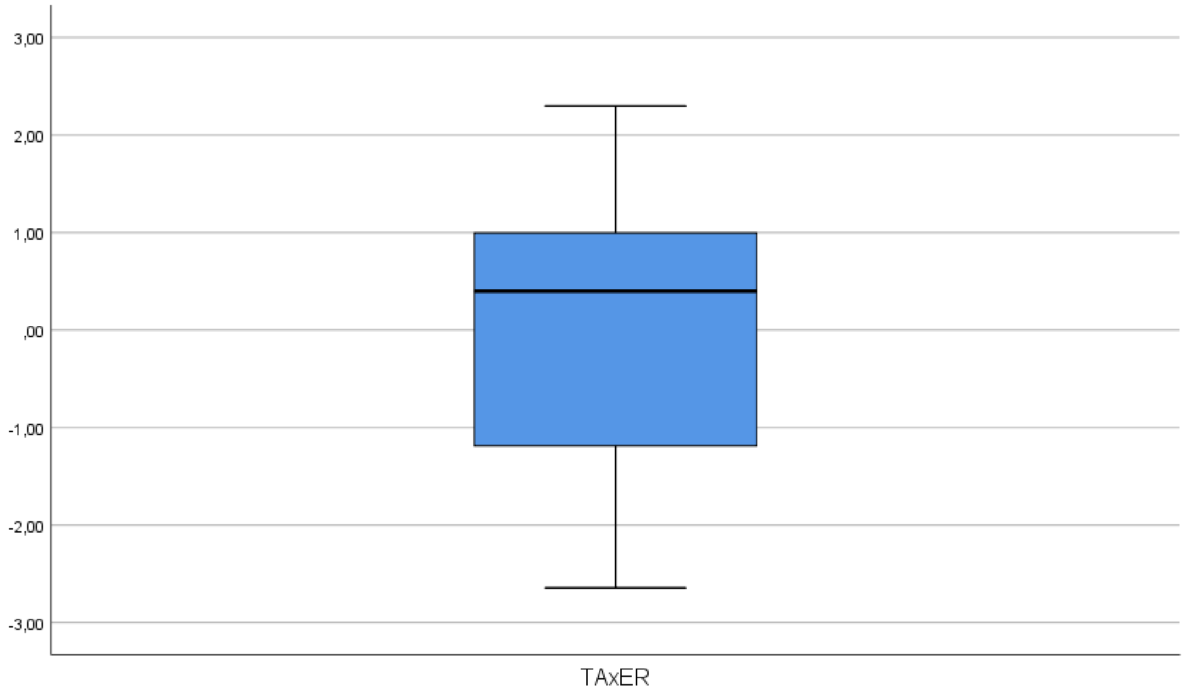

Figure 6: Boxplot of the relationship between air temperature and ecosystem respiration. Outliers are indicated with a dot separate from the box and the whiskers.

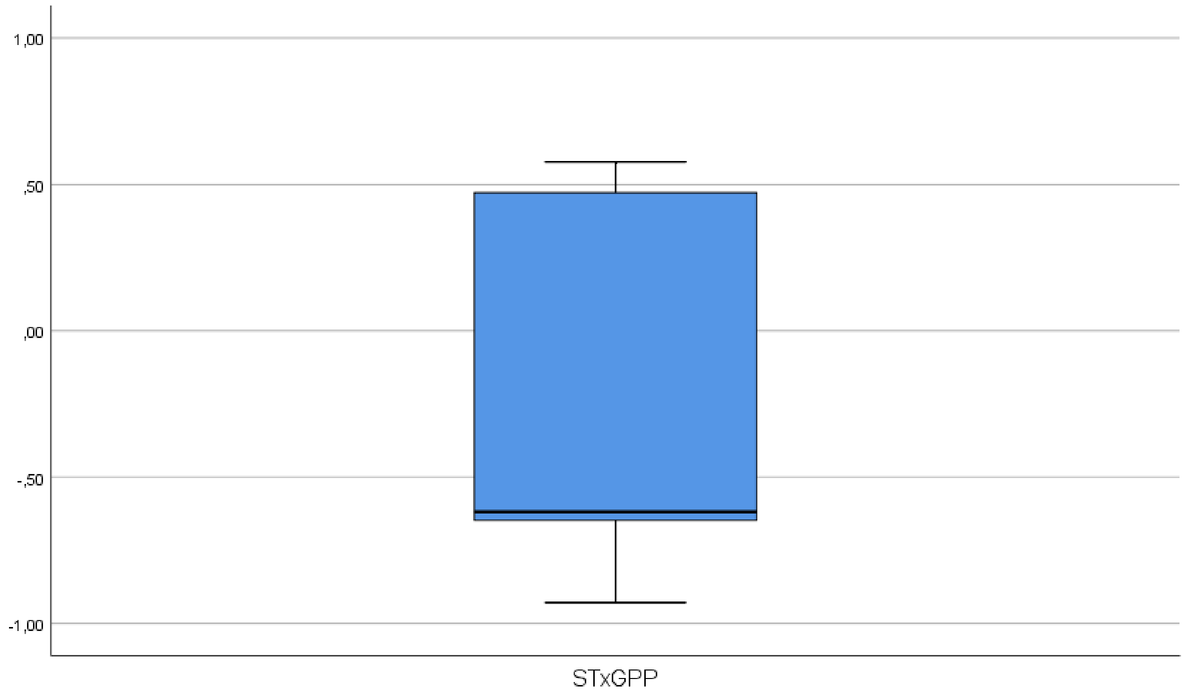

Figure 7: Boxplot of the relationship between soil temperature and GPP. Outliers are indicated with a dot separate from the box and the whiskers.

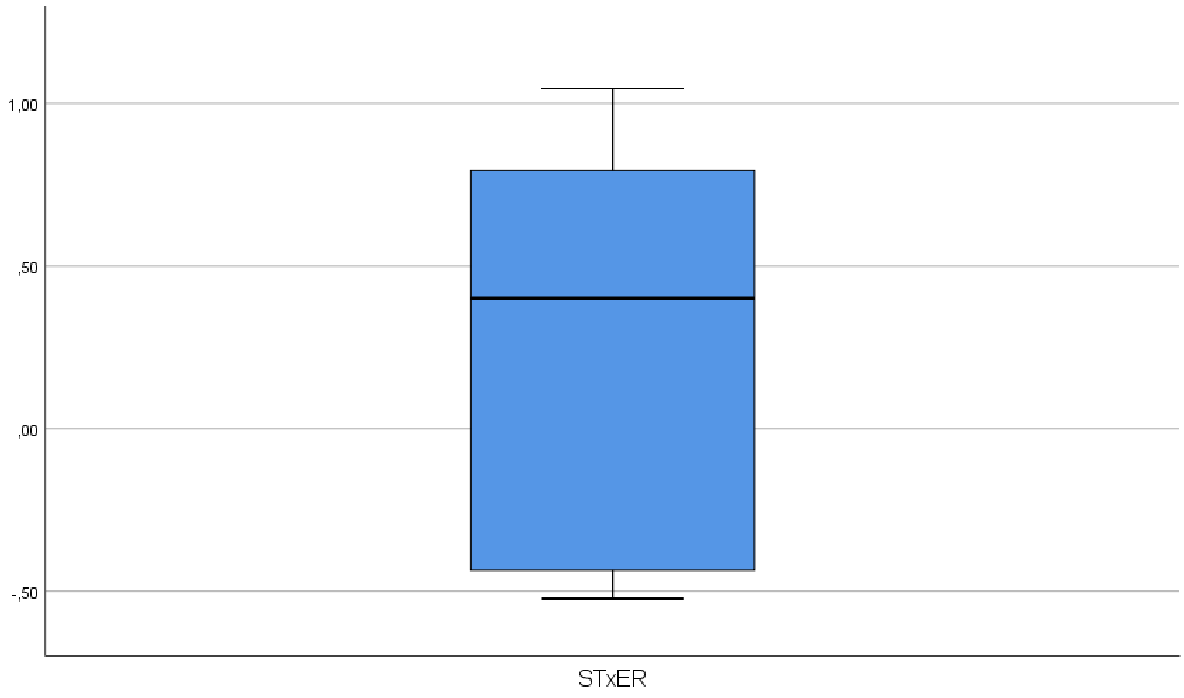

Figure 8: Boxplot of the relationship between soil temperature and ecosystem respiration. Outliers are indicated with a dot separate from the box and the whiskers.

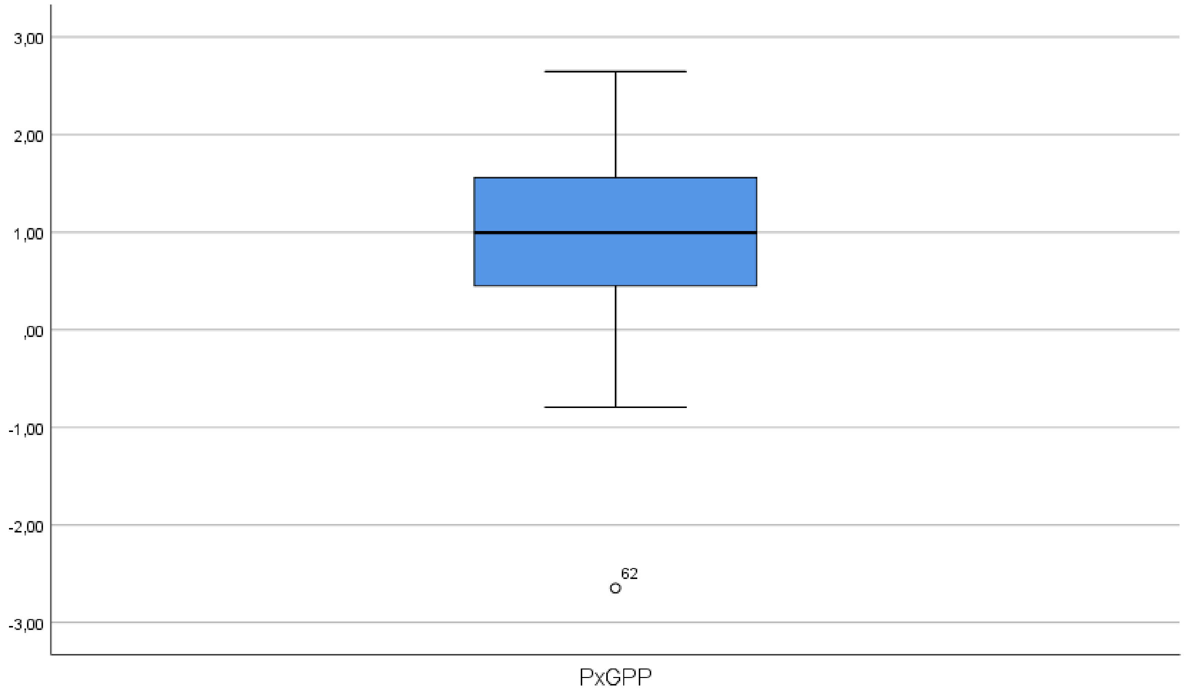

Figure 9: Boxplot of the relationship between precipitation and GPP. Outliers are indicated with a dot separate from the box and the whiskers.

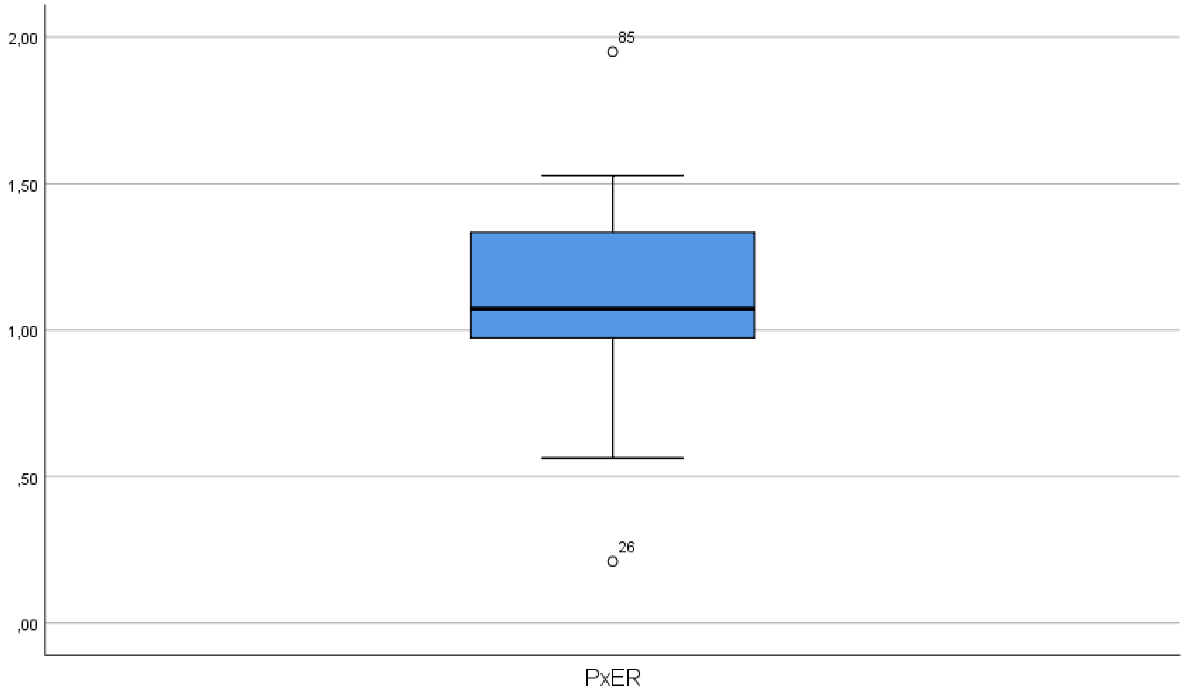

Figure 10: Boxplot of the relationship between precipitation and ecosystem respiration. Outliers are indicated with a dot separate from the box and the whiskers.

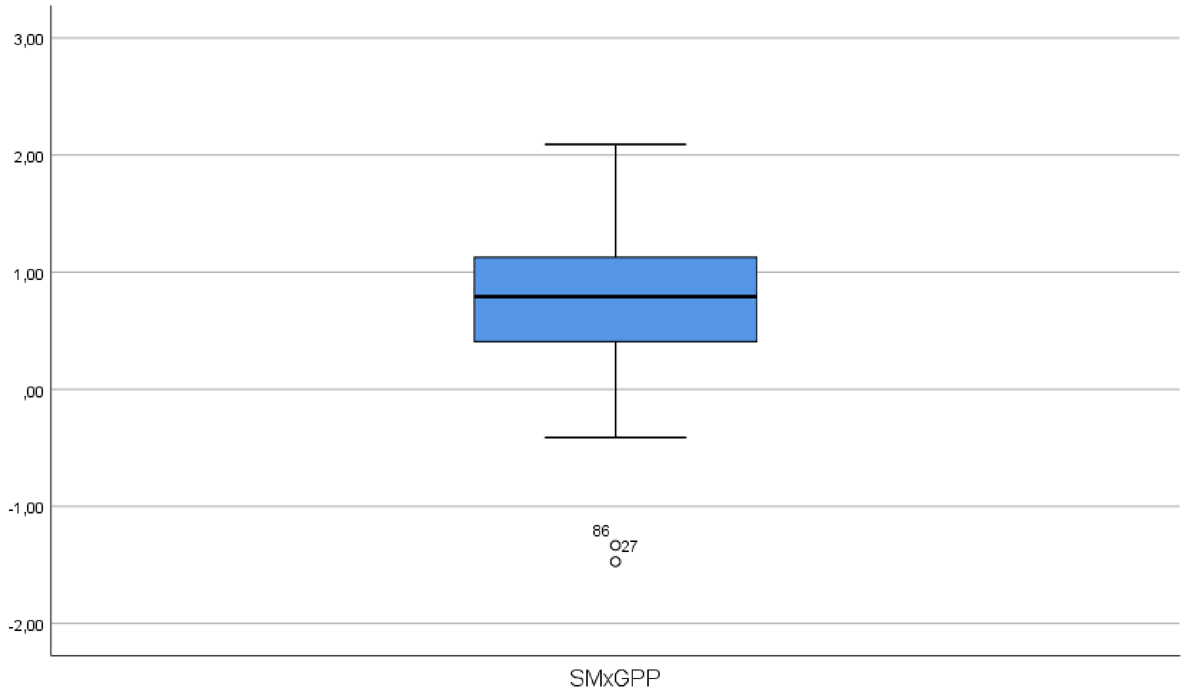

Figure 11: Boxplot of the relationship between soil moisture and GPP. Outliers are indicated with a dot separate from the box and the whiskers.

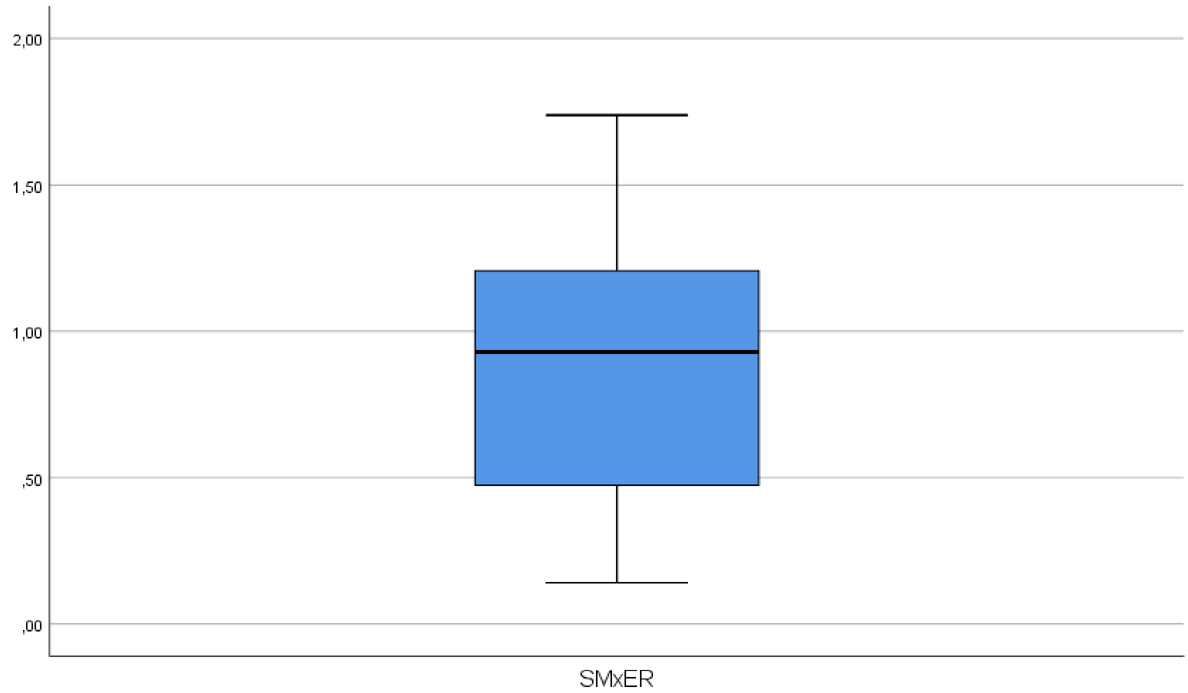

Figure 12: Boxplot of the relationship between soil moisture and ecosystem respiration. Outliers are indicated with a dot separate from the box and the whiskers.

C. Numerical results of descriptive statistics

Table 5: Descriptive statistics of the non-partitioned relationships.

	TxGPP	TxER	WxGPP	WxER
N	21	25	33	24
Mean	0.2589	0.0880	0.7976	1.0154
Minimum	-1.66	-2.65	-1.47	.14
Maximum	2.30	2.30	2.65	1.95
Std. Deviation	1.07343	1.23474	.91288	.44928

Table 6: Descriptive statistics of the partitioned relationships

TAxGPP	TAxER	STxGPP	STxER	PxGPP	PxER	SMxGPP
16	17	5	8	14	14	18
0.4114	0.0095	-0.2292	0.2549	1.0692	1.0826	.7125
-1.66	-2.65	-.93	-.52	-.79	.21	-1.33
2.30	2.30	0.58	1.05	2.65	1.95	2.09
1.14090	1.44595	0.69941	0.63363	0.85141	0.43482	0.80181

D. Analysis of Variance: Levene Statistics

Table 7: Results of Levene's test. A dash indicates that one of the two grassland types had only one observation, therefore Levene statistic could not be computed.

Relationship	Leven Statistic	Significance	Test
TAxGPP	-	-	ANOVA
TAxER	1.641	0.269	ANOVA
STxGPP	1.824×10^{30}	0.000	Brown-Forsythe
STxER	4.702	0.082	ANOVA
PxGPP	-	-	ANOVA
PxER	0.879	0.376	ANOVA
SMxGPP	3.468	0.095	ANOVA
SMxER	32,906	0.011	Brown-Forsythe