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# Long-Term Response of Floodplain Meadow Normalized Difference Vegetation Index to Hydro-Climate and Grazing Pressure: Tamir River Plains, Mongolia

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**Abstract:** The greenery of floodplain meadows in arid regions, such as Mongolia, is influenced by climate, hydrology, and land use. In this study, we analyzed the NDVI (Normalized Difference Vegetation Index) of two floodplain meadows located along the South Tamir and Tamir Rivers using LANDSAT images. Our goal was to observe NDVI spatial changes, variations, and mean values in mid-August every six years from 1991 to 2015 and to identify the factors driving these differences. To achieve this, we conducted variance analysis to identify changes in NDVI and implemented Principal Component Analysis to determine the influence of hydro-meteorological factors and grazing intensity. Our findings indicate a significant decrease in greenness, as measured by pixel-scale NDVI, during the late summer period. This decrease was consistently observed, except for a series of harsh winters that followed relatively dry summers, resulting in a disastrous event called *dzud*, which led to the death of livestock. The decrease in NDVI was amplified by lower precipitation in June, higher temperatures and wind speed in July, and increased precipitation in August, along with a higher frequency of days with convective rain. Our findings have important implications for managing grazing in Mongolia's grasslands, promoting sustainable land use, and mitigating sandstorms. The variance and average values of NDVI at the pixel level can serve as reliable markers of sustainable pasture management in areas where other vegetation measures are limited.

**Keywords:** NDVI; climate change; hydro-climatic factors; grazing intensity; *dzud* events; floodplains; Mongolia

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## 1. Introduction

Floodplains are flat areas periodically inundated due to lateral overflow from rivers, groundwater, highland sources, and direct precipitation [1] that serve regulatory, habitat, production, aesthetic, and cultural functions [2], making them ideal for wildlife and human settlements [3]. Nonetheless, floodplains face a variety of stressors, including global climate change and alterations to land use patterns [4–6].

Variations in precipitation and temperature can modify the accessibility of water supplies for vegetation in floodplains [7]. Increased frequency and intensity of rainfall can lead to increased flood frequency, duration, and magnitude [8]. Decreased flooding may result in reduced soil fertility [9], diminished habitat variability [10], and increased competition from invasive species [11], affecting the diversity and resilience of floodplain ecosystems [12]. Elevated temperatures enhance evaporation from water bodies and soil surfaces, especially in dry and semi-arid areas [13]. Aggravating drought conditions will

reduce soil moisture, potentially leading to shifts in plant phenology and growth, as well as species composition and overall productivity in floodplain meadows [14].

Grazing can exert both beneficial and detrimental effects on the level of vegetation cover in floodplains. Moderate grazing can preserve the diversity and composition of vegetation by preventing the dominance of some plant species and promoting the growth of others [15]. Intensive grazing can result in the depletion of tall grasses and woody plants, promoting the growth of small grasses and forbs [16], as well as causing soil compaction and erosion [17].

Mongolia covers an area of 1.56 million km$^2$, and about 90% is suitable to be used as rangeland. Air temperatures have climbed 2.24 °C since 1960 [18], and livestock populations have increased since 1990. The Normalized Difference Vegetation Index is used to evaluate the influence of these parameters on the vegetation cover [19]. Some research suggests that grazing pressure dramatically reduces vegetation greenness [20], and other studies have stressed the importance of climatic factors like rising temperatures [21] and precipitation [22,23]. These studies frequently covered large areas like Mongolia or the Mongolian Plateau, but they often ignored specific ecosystems like floodplains, which are crucial to livestock grazing dynamics. Furthermore, there are no available data regarding the recovery of vegetation following a livestock mass mortality event, *dzud*.

The *dzud* is an extreme winter condition that leads to high mortality of livestock [24] and can have devastating effects on the livelihoods of Mongolian herders [25]; it can be particularly severe when it follows a summer drought and occurs in subsequent years [26]. The subsequent three years of *dzud* from 1999 to 2002 were the worst disaster [27] out of the 10 *dzud* events that have happened since 1944 [28]. It caused 30% of the total national livestock to perish [25]; in contrast, during the most recent such event, which occurred in the winter of 2009–2010, 20% perished [24]. The time between the dieback of livestock and the recuperation of the herds serves as a resting period for the vegetation, which gives the possibility to assess its resilience. During the centrally planned period, livestock numbers were kept under 25 million, whereas in 2015, there were about 56 million animals [29], and with a higher increase in the target region of the study compared to other parts of the country [30], making it sensitive to *dzud* [25].

The floodplain meadows found alongside large rivers account for around 5% of the overall extent of rangeland, as reported by Tserendash and Bilegt in 2017 [31]. Although floodplains are small in size, they are intensively utilized for grazing and hay gathering. Pastoralists strategically confine their animals to the plains and nearby areas to conserve the highland pastures for the other seasons. This is because the meadow vegetation grows rapidly throughout the summer due to the abundance of water, nutrient enrichment, warm temperatures, and species adaptations. However, variations in water flow, both within and between years [32], and the reduced maximum water flow of the main rivers in the Selenge basin in Mongolia could potentially result in the degradation of wetlands and moist habitats [33]. Tserendash and Bilegt [31] reported a decrease in the number of plant species and pasture productivity in the Selenge basin meadows over the past few decades. Additionally, a significant loss in soil infiltration has been documented in the floodplains of eastern Mongolia [34].

Monitoring the establishment and recovery of vegetation in floodplains is essential for assessing the management needs of flow regimes and the success of restoration initiatives in river systems worldwide [35–37]. Empirical evidence about the differences in hydrologic and edaphic conditions along slopes, both geographically and temporally, is insufficient. Furthermore, the relationship between these variables and vegetation characteristics is still unclear [38]. This holds especially true for the biomass and diversity of herbaceous floodplain vegetation in arid and semi-arid regions such as Mongolia, where there is a lack of meteorological, hydrological, and groundwater monitoring stations [39], as well as insufficient personnel and financial resources [3].

This study aimed to examine the impact of hydro-climatic variables and grazing pressure on variation in the greenness of floodplain meadows. We examined NDVI fluctuations

at two meadow sites adjacent to the Tamir River system every sixth year between 1991 and 2015. Given the noted decrease in runoff in the Selenge basin's main rivers since the mid-1990s [33] and the ongoing rise in livestock numbers, our study sought to test the following hypotheses. Hypothesis (1): Floodplain meadows experienced a decrease in NDVI from 1991 to 2015 due to reduced moisture levels and increased grazing pressure. The country lost 10 million animals out of a total of 33 million due to the three consecutive *dzud* events in 1999–2002 [25]. Hypothesis (2): Floodplain meadows experienced a higher NDVI in 2003 compared to 1997 as a result of decreased grazing intensity.

## 2. Materials and Methods

### *2.1. Study Area*

The South Tamir (165 km long, catchment area of 2470 km$^2$) and North Tamir (180 km long with a catchment area of 2990 km$^2$) rivers originate from the Khangai mountain range and pass through the forest-steppe zone (Figure 1) where the average annual precipitation ranges from 300 to 400 mm and temperature between 1.3 and 7.2 °C [40]. After these two rivers unite, the Tamir River drains into the Orkhon River after 50 km. The rivers are unregulated and rainfed. Their flow fluctuates greatly due to the dry climate, and they freeze to the bottom over winter [32]. Between the intervals 1978–1995 and 1996–2015, the mean annual temperature increased by 0.86 °C, mean runoff decreased by around 50%, while precipitation decreased insignificantly [33], and convective rain events became more frequent [41]. Grazing is the main type of land use, especially in the floodplains.

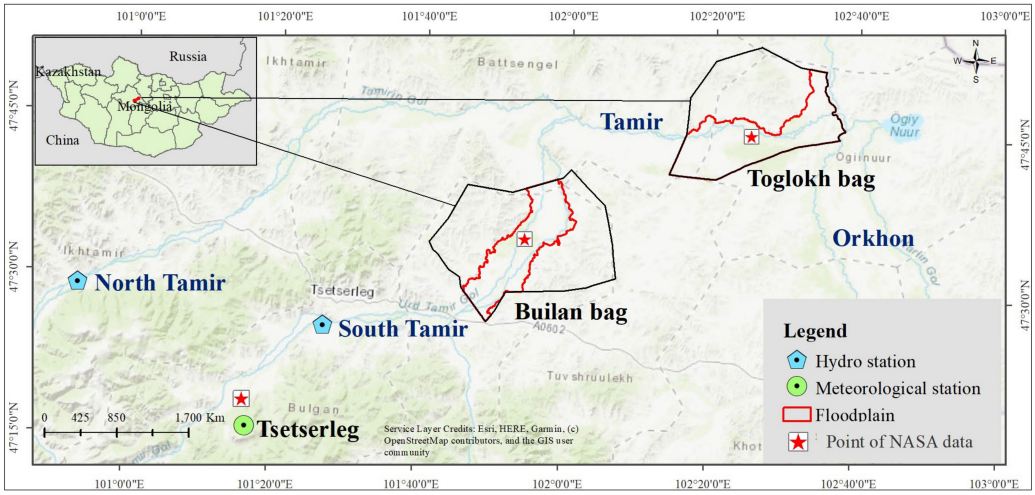



**Figure 1.** Image of the study area with the nearest hydrological and meteorological stations and points of NASA/POWER data. Red lines indicate the boundaries of each floodplain. Black lines indicate the rest of the *bag* boundaries. The inset map shows the position of the study area on a world topographic map.

We chose the Builan *bag* (the smallest administrative entity) in the South Tamir River plain and the Toglokh *bag* in the Tamir River (Figure 1). They are more than 20 km apart at their closest point. These two *bag*s were chosen for the following reasons: (1) Floodplains cover roughly half of their territories, with slopes accounting for the rest. (2) Their territories are equivalent in size and terrain characteristics: Builan's area is 624,820 ha (170,097 hectares of floodplain habitat) at 1690 m a.s.l., whereas Toglokh's territory is 512,750 ha (217,260 ha of floodplains) at 1530 m a.s.l. (3) The availability of satellite photos without cloud effects.

### *2.2. Satellite Data*

Despite LANDSAT 4–5 TM and 8 OLI_TIRS images having a low occurrence, they are ideal for evaluating NDVI changes across smaller areas such as floodplains, as opposed to MODIS, which is most commonly employed in vast arid regions After conducting an

extensive study of several images available on the USGS official website[1], we have selected certain images (row/path: 027/134) captured over the time period of 17–19 August, with a six-year interval, specifically in the years 1991, 1997, 2003, 2009, and 2015. The mid-August timeframe corresponds to the end of the growing season, during which vegetation has reached its full maturity. The coefficient of variation of NDVI in Arkhangai province, which is our target region, exhibited the lowest seasonal dynamics (0–10%) [42]. Furthermore, the photos contained less than 10% cloud cover. Ultimately, our intention was to observe the year 2003, which succeeded significant *dzud* events that occurred throughout this time period, in order to determine if the decreased number of animals led to the recovery of NDVI.

The floodplain boundaries of the two *bag* territories were trimmed using a riparian area digital elevation model demarcation shape file generated by WWF [43]. Image processing was analyzed using ENVI 5.3 and ArcGIS 10.5 software. The NDVI spatial patterns were created using the Raster package of R.

NDVI has been used to indicate rangeland degradation [44,45], long-term vegetation changes, and land use changes at regional, national, and biome scales [42]. NDVI values vary from −1.0 to 1.0, with negative values indicating clouds and water, positive values near zero suggesting bare soil, and higher positive values indicating sparse vegetation (0.1–0.5) to dense green vegetation (0.6 and above) [46]. The NDVI is the difference between the NIR and RED bands, normalized by their sum.

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (1)$$

### 2.3. Meteorological Data

Due to the limited number of meteorological stations in our study area and the incompleteness of the data series, we utilized the data from NASA's Prediction of Worldwide Energy Resources (NASA/POWER; power.larc.nasa.gov accessed on 13 December 2022)[2] project. This dataset encompasses a wide range of meteorological factors that have the potential to influence vegetation growth. Solar radiation (SRAD) is determined by utilizing satellite data and atmospheric variables on a global scale with a grid resolution of $1^\circ \times 1^\circ$ [47]. When ground weather station data is unavailable or scarce, NASA/POWER can be useful in generating weather datasets. [48]. From 1995 to 2008, the daily air temperature (R = 0.99, $p < 0.0001$, df = 5113) and precipitation (R = 0.80, $p < 0.0001$, df = 5113) at the local station Tsetserleg closely corresponded to the data provided by NASA/POWER (Figure 1).

We gathered temperature, precipitation, and wind data for 107 days between 1 May and 15 August (Table 1) because NDVI is influenced by meteorological conditions in the preceding months. Monthly data were derived from daily data. The 107 days were categorized as rainless, stratiform, and convective rain days.

**Table 1.** Monthly mean meteorological values and trends between 1991 and 2015 for the floodplains. T = temperature, P = precipitation, and W = wind speed. The Mann–Kendall trend test was calculated. Minus (−) signs indicate decrease. All $p > 0.05$.

| **Floodplain** | | **May** | | **June** | | **July** | | **August** | |
|---|---|---|---|---|---|---|---|---|---|
| | | ***z*** | ***slope*** | ***z*** | ***slope*** | ***z*** | ***slope*** | ***z*** | ***slope*** |
| Builan | T | −0.142 | −0.053 | 0.022 | 0.007 | 0.087 | 0.021 | 0.203 | 0.080 |
| | P | −0.051 | −0.091 | −0.080 | −0.394 | 0.007 | 0.210 | 0.123 | 0.311 |
| | W | 0.106 | 0.009 | −0.131 | −0.008 | 0.055 | 0.002 | 0.072 | 0.007 |
| Toglokh | T | −0.174 | −0.059 | −0.007 | −0.001 | 0.087 | 0.015 | 0.181 | 0.077 |
| | P | −0.029 | −0.074 | −0.159 | −0.545 | −0.014 | −0.103 | 0.188 | 0.474 |
| | W | 0.080 | 0.004 | 0.029 | 0.002 | 0.157 | 0.005 | 0 | −0.001 |

Note: August measurements cover the first half of the month since we calculated NDVI between 17 and 19 August. *z*—Mann–Kendall test; *slope*—Sen's slope.

We obtained daily runoff data for the South and North Tamir Rivers from the National Agency for Meteorology and Environmental Monitoring. Subsequently, we computed the monthly minimum, mean, and maximum discharge throughout the growing season. In the Builan plain, we used data from the South Tamir gauge, and for the Toglokh, data from both the South and North Tamir gauges because the plain is situated in the Tamir plain downstream from the confluence of these two rivers.

### *2.4. Grazing Data*

Data on livestock numbers were accessible at the *bag* scale only after 2003. The livestock number from 1991 to 2002 was estimated using a linear regression model based on soum (administration unit above the *bag*)-scale data. The regression coefficient was 0.98–0.99. The total number of livestock was calculated using a conversion suggested by the National Statistics Office, in which large animals such as cattle and horses were recalculated to the equivalent number of sheep units based on fodder supply and pasture carrying capacity (1 horse = 7 sheep, 1 head of cattle = 6 sheep, 1 goat = 0.9 sheep) [29]. Grazing intensity (GI) was assumed to be spatially uniform and computed using the same ratio of sheep units per area as in previous studies [49]. Based on livestock density, we classified up to 2 head of sheep per hectare as light GI, 2–4 as moderate, 4–6 as heavy, and more than 6 as extreme GI. Currently, we do not have regulations and standards to define the GI in Mongolia. Therefore, we classified the GI based on comparable studies in neighboring regions in China [23], which suggest a moderate GI for better pasture use practices [50,51].

### *2.5. Statistical Analysis*

The general workflow of the statistical analyses is illustrated in Figure 2.

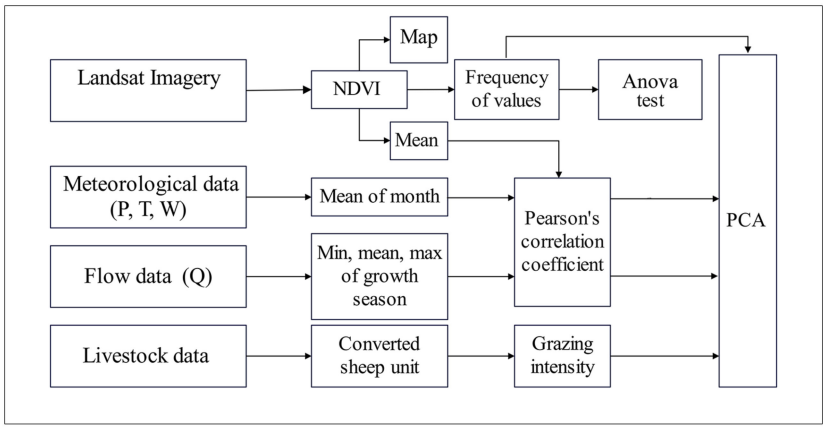



**Figure 2.** A conceptual flow chart of the statistical workflow.

The coefficient of variation of NDVI, mean NDVI change, and test for relationships between NDVI values and hydro-climatic variables were calculated using SPSS. Mean NDVI change was tested by the Tukey multiple comparison statistic for pair-by-pair contrasts [52].

Principal Component Analysis (PCA) was conducted to illustrate the general pattern of the parameters such as NDVI values, the hydro-climatic variables, and GI using CANOCA [53]. Linear regression was used to test for relationships between mean NDVI and livestock density.

## 3. Results

### *3.1. NDVI Change*

Pixel-level NDVI values in the two floodplains declined from 1991 to 2015 (Figure 3). Over time, high NDVI values (>0.4) consistently decreased. The values of 0.7 and 0.8 no longer existed by 2015. As a result, the maximum values shifted from approximately 0.45 to around 0.25, which was the prevailing value for the adjacent highland steppes. Additionally,

the area covered by a certain range of NDVI values shifted greatly over time (Figure 3, bar charts). For example, areas covered by 0.3 values increased by 22 times in Builan and 44 times in Toglokh, while areas covered by 0.6 values decreased by 23 times in Builan and 17 times in Toglokh. Finally, the NDVI variability increased in 1997 and 2003 and decreased in 2009 and 2015 for both plains (Table 2).

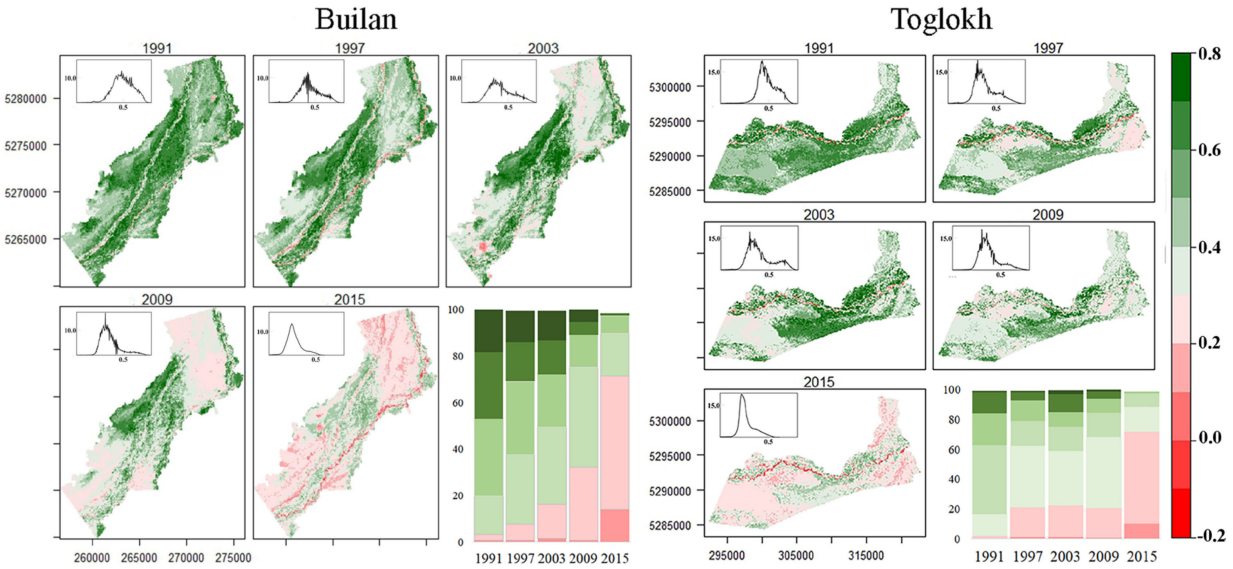



**Figure 3.** The spatial difference of pixel−level NDVI changes in Builan and Toglokh *bag*s for every sixth year from 1991 to 2015. The inset histograms illustrate NDVI value frequencies. Bar charts summarize the changes in areas covered with specific NDVI values for the census year.

**Table 2.** Coefficient of variation of the NDVI values for each year in Builan and Toglokh.

| Years | 1991 | 1997 | 2003 | 2009 | 2015 |
|---|---|---|---|---|---|
| Builan | 0.013 | 0.015 | 0.018 | 0.011 | 0.007 |
| Toglokh | 0.011 | 0.015 | 0.019 | 0.012 | 0.007 |

The mean NDVI in Builan has significantly decreased over the years. The largest decrease was observed in 2015, compared to 2009, with a comparatively smaller decrease in 2003. As for Toglokh, the most notable decrease occurred in 1997 and 2015, compared to 1991 and 2009. The NDVI remained relatively constant during the low-flow years. However, there was a significant increase in 2003, compared to 1997 (Figure 4, Table 3).

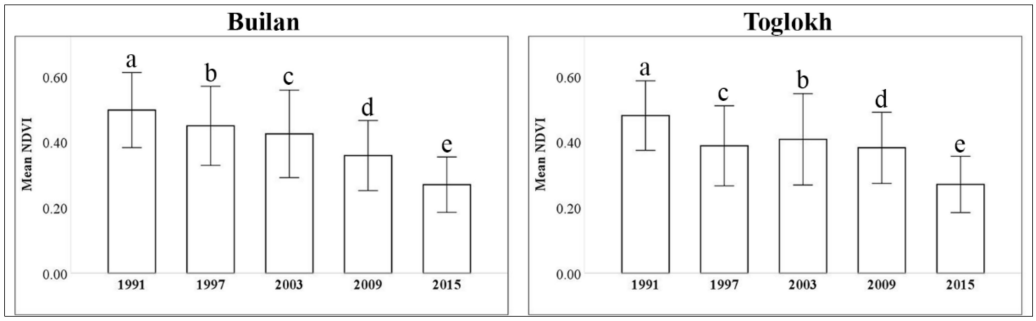



**Figure 4.** Mean NDVI change over time for the two *bag*s. The error bar stands for standard deviation. Bars with different lowercase letters are significantly different ($p < 0.001$) according to Tukey tests.

**Table 3.** Differences in mean NDVI values between any two years. The *p*-values for each test are below 0.0001. The standard error is 0.00022 for Builan and 0.000199 for Toglokh. A minus sign (−) indicates increased NDVI, while the others indicate decreased NDVI.

| | Builan | | | | Toglokh | | | |
|---|---|---|---|---|---|---|---|---|
| **Year** | **1997** | **2003** | **2009** | **2015** | **1997** | **2003** | **2009** | **2015** |
| 1991 | 0.048 * | 0.073 * | 0.139 * | 0.227 * | 0.092 * | 0.072 * | 0.098 * | 0.221 * |
| 1997 | | 0.024 * | 0.090 * | 0.179 * | | −0.019 * | 0.006 * | 0.118 * |
| 2003 | | | 0.066 * | 0.155 * | | | 0.026 * | 0.138 * |
| 2009 | | | | 0.089 * | | | | 0.112 * |

* The mean difference is significant at the 0.05 level.

### *3.2. Driving Factors*

#### 3.2.1. Climatic Factors

The NDVI values correlated significantly with climatic parameters ($p < 0.05$) but insignificantly with flow variables ($p > 0.05$). While NDVI was positively influenced by precipitation in June and the occurrence of stratiform rainfall throughout the growing season, it was negatively impacted by the hot and windy conditions in July and the rainfall in August (Table 4).

**Table 4.** Pearson correlation of the mean NDVI and hydro-climatic factors.

| **Factors** | **May** | **June** | **July** | **August** | **June to August** |
|---|---|---|---|---|---|
| Q min. | - | - | - | - | 0.409 |
| Q mean | - | - | - | - | −0.102 |
| Q max. | - | - | - | - | −0.051 |
| Temperature | 0.293 | 0.580 | −0.766 ** | −0.077 | - |
| Precipitation | −0.246 | 0.688 * | 0.129 | −0.751 * | - |
| Wind speed | −0.150 | −0.169 | −0.643 * | −0.507 | - |
| No rain days | - | - | - | - | −0.569 |
| Stratiform rain days | | | | | 0.666 * |
| Convective rain days | | | | | −0.503 |

* and ** represent $p < 0.05$ and $p < 0.01$, respectively.

#### 3.2.2. Grazing Intensity

The mean NDVI and livestock density exhibited a negative correlation in both plains, with a stronger correlation observed in Builan ($R_{Builan} = 0.97$, $R_{Toglokh} = 0.77$). The number of livestock in Builan increased 5.1 times, while Toglokh experienced a 3.1-fold increase (density of 2.7 and 1.7) during the period from 1991 to 2015 (Figure 5). In the initial *dzud* years (winters of 1999–2002), the mortality rate in Builan was 33%, whereas in Toglokh, it was 60%. However, during the second *dzud* period (winter of 2009–2010), the mortality rates changed to 55% in Builan and 11% in Toglokh (Figure 5).

The eigenvalues for axis 1 and axis 2 are 0.83 and 0.12, respectively. This suggests that climatic factors have a greater influence than hydrological factors. Higher NDVI values (0.5–0.8) in 1991 were influenced by high flows, June temperatures, June precipitation, and stratiform rains, while the impact of moderate grazing intensity was relatively less significant. In the low-flow years between 1997 and 2009, NDVI values gradually decreased with the dominance of values 0.4 and 0.3. By 2009, heavy grazing intensity competed with adverse climatic factors such as the number of convective rain days and wind. In 2015, extreme grazing intensity and aridity were the main factors influencing NDVI values, despite the increase in flow (Figure 6).

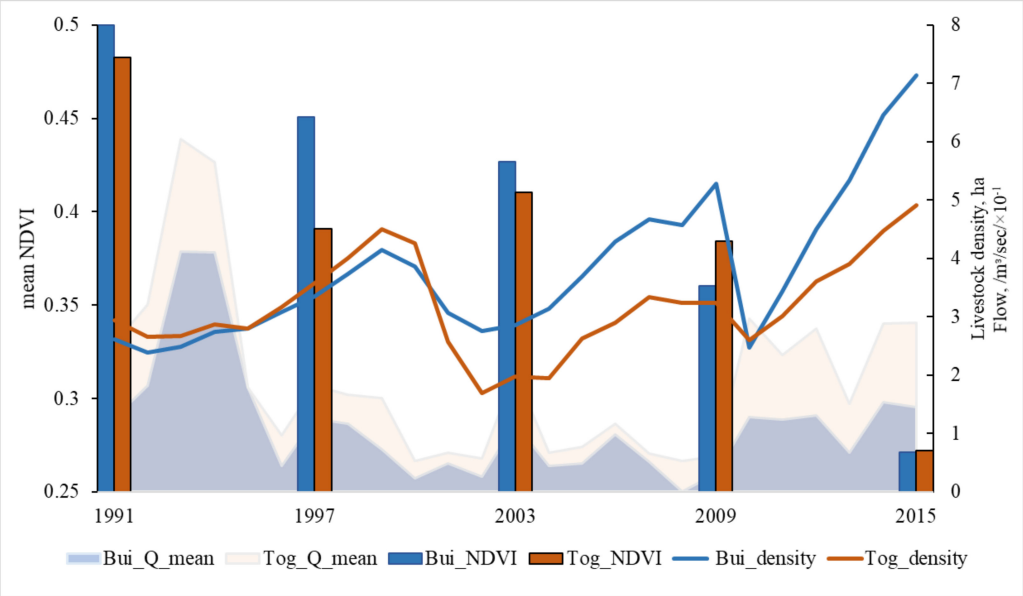



**Figure 5.** Comparison of the mean NDVI with the yearly livestock density and summer mean flow. If the density is up to 2 head of sheep per hectare, the GI is light, 2–4 is moderate, 4–6 is heavy, and more than 6 is extreme. The years 1991–1995 were high, 1996–2009 were low, and 2010–2015 were medium−flow years.

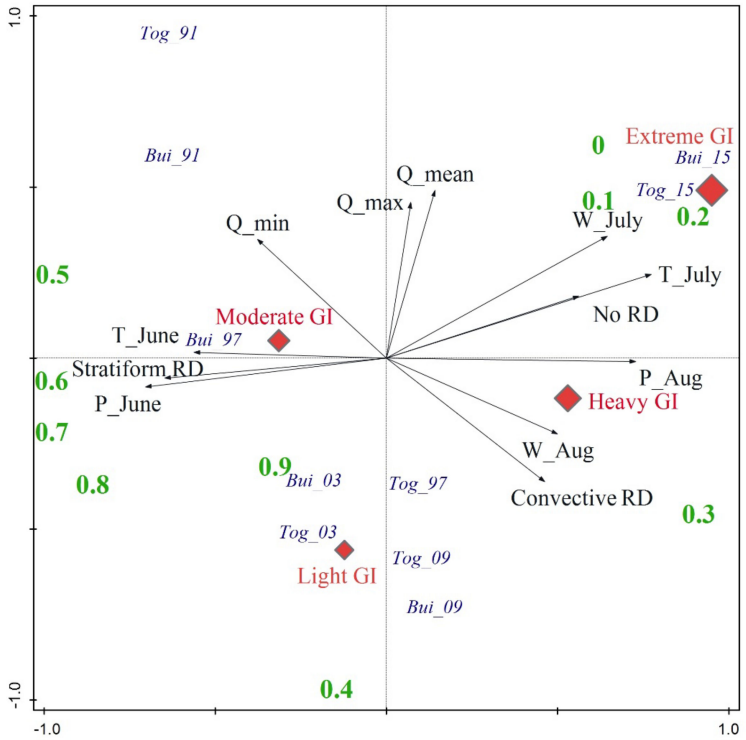



**Figure 6.** The PCA ordination of two floodplains (Tog = Toglokh *bag*, Bui = Builan *bag*) with data from every 6 years from 1991 to 2015. Green numbers = NDVI values, Q = runoff, T = temperature, *p* = precipitation, W = wind, RD = rain days, GI = grazing intensity.

## 4. Discussion

Floodplain plant community structure is largely influenced by flow and sediment characteristics, in addition to the general factors that affect upland communities [54,55]. This is true for high-order large river floodplains where flooding is predictable [56]. In medium-

sized rivers in arid and semi-arid regions, such as the Tamir Rivers, flows vary significantly from year to year [57], and flood events are unpredictable [58], resulting in riparian vegetation being more influenced by local climatic factors and land use [59]. This may be particularly relevant for riparian vegetation, which is impacted by a warming climate [60]. From 1991 to 2015, flows of the South Tamir and Tamir Rivers fluctuated greatly. This time can be divided into high (1991–1995), low (1996–2009), and medium (2010–2015) flow periods.

Average flow during the high-flow period was 28.2 $m^3/s$ for Builan and 43.6 $m^3/s$ for Toglokh. Most areas of the plains were covered by high NDVI values (0.5–0.8) and showed less variability. This can be attributed to the precipitation and temperature in June, as well as the occurrence of stratiform rain days, which promote strong hydrological connections in the plains. Both Builan and Toglokh plains experienced moderate grazing intensities, and grazing did not have a significant impact on the NDVI compared to the hydro-climatic factors during this period (Figure 6). In 1991, Mongolia transitioned to a market economy, leading to the return of livestock from state collectives to private ownership by herders.

The NDVI values in 1997, 2003, and 2009 were defined during the low-flow period. The average flow decreased to 6.1 $m^3/s$ for Builan and 10.2 $m^3/s$ for Toglokh. This aligns with reports stating that runoff from all major rivers in the Selenge basin, including the Tamir River, has significantly decreased since 1996 [33]. Furthermore, a downward trend in precipitation has been observed across the Mongolian Plateau since the mid-1990s, resulting in a decrease in NDVI during the growing season [61]. The sharp decrease in the Toglokh plain in 1997 may be attributed to the separation of the relatively elevated and far extended parts from the river bank. These parts of the plain are susceptible to low flow conditions and can easily become disconnected from the hydrological network. The majority of the Builan plain runs parallel to the river bank.

The characteristics of NDVI in 2003 were unique. The highest variation in NDVI (Table 2) can be attributed to the introduction of plant communities with low NDVI values, around 0.4, due to reduced flow; meanwhile, the plain still sustains communities with high NDVI values with equal contribution. Studies conducted in the larger Selenge basin floodplains indicate that plant community associations have become less diverse due to significant changes in species composition and vegetation types. For example, plant productivity decreased fourfold from 2004 to 2013 compared to the average from 1976 to 1990, and the *Sanguisorba–Elymus–Bromus* association was replaced by an *Elymus*-dominated *Carex–Artemisia–Elymus* association [31]. The smallest difference in mean NDVI between analyzed years and even the significant recovery for the Toglokh plain's greenness (Table 3) can be explained by the sharp decrease in grazing intensity caused by the three years of drought–*dzud* disasters (1999–2000, 2000–2001, 2001–2002), which resulted in the loss of 33% of animals in Builan and 60% in Toglokh. This suggests that if grazing intensity remains low, the floodplain's NDVI is able to recover during low-flow years. By 2009, NDVI variation had decreased due to the further intrusion of vegetation with lower NDVI values into the communities and increased grazing pressure, specifically in the Builan plain. Both the NDVI and the number of animals in the Toglokh plain reached the same level as in 1997 (Figure 5). The consistent record provides strong evidence of the relationship between NDVI and grazing intensity during low-flow period in this plain.

Medium flow rates of 12.4 $m^3/s$ for Builan and 25.7 $m^3/s$ for Toglokh were maintained from 2010 to 2015. However, the lowest variation in NDVI and the highest difference in mean NDVI were observed in 2015 for each plain. This can be attributed to the combined impact of more pronounced climate change and increased grazing intensity. Firstly, climate change is evident in a decrease in May temperatures and an increase in summer months, particularly in July. The Tamir River basin experiences the highest recorded summer temperature changes in the Selenge basin [33] and in all of Mongolia [41]. Secondly, precipitation changed in terms of amount, seasonal allocation, and type. Precipitation in June and July decreased, while that in August has increased with convective rains leading to an increase in flow. Late-summer precipitation, subsequent flooding, and higher groundwater

levels may be more detrimental to vegetation since plants in regions with a short growing season may have already shifted their development stage to favor storage rather than growth [62,63], in addition to the relationship between precipitation and available sunshine hours for photosynthesis [64]. Other studies have revealed that densely vegetated areas on the Mongolian Plateau are particularly vulnerable to variations in precipitation [20]. There has also been a notable increase in the number and duration of convective rains in the Khangai mountain range and northern Mongolia [41,65]. Furthermore, wind intensity in July and August has also affected the NDVI in the Tamir basin. Wind erosion is a major contributor to land degradation and desertification, affecting approximately 90% of the land area in Mongolia to some extent [66]. Additionally, wind can accelerate evapotranspiration [67] and cause damage to leaves or young plants through abrasion [68], altering their chemical composition, physical structure, and morphology at various scales, from the cellular level to the entire plant [69]. Reduced soil infiltration, caused by the disruption of the hydrological network during low-flow years [6], causes followeda decrease in groundwater tables, as recorded in regional plains like Orkhon [39], and a loss of mesic habitat diversity as a result of decreased runoff due to increased temperature and accelerated evapotranspiration [33,70].

Between 1991 and 2015, the Tamir River floodplain meadow NDVI was negatively affected by warming climatic factors, which were made worse by overgrazing. Since 1963, the country has seen a 2 °C increase in average annual temperatures, along with higher maximum temperatures, and a 7% decrease in precipitation [71]. Additionally, there have been more frequent heavy-rain events [67]. Moreover, climate-related risks like droughts, heatwaves, and extreme-cold *dzud* events have become more common [30], leading to a significant loss of livestock due to lack of food and prolonged freezing temperatures [25]. *Dzud* impacts are especially severe when low-production summers caused by drought are followed by extremely cold winters, particularly when this pattern occurs over multiple years [27].

Grazing is the predominant land use in the target plains, and floodplains are particularly susceptible to increased grazing pressure [72]. During the socialist era, the meadows in the Orkhon–Selenge basin were primarily preserved for hay harvest [31]. However, after livestock privatization in the early 1990s, the number of animals skyrocketed, tripling by 2015 at a national level, especially in the forest-steppe region and major river valleys, and summer rangelands along the floodplains tend to be more degraded compared to winter pastures [40]. Besides the increased number of livestock, the animal husbandry system became vulnerable due to pasture degradation, *dzud* events, and the loss of formal regulations and traditional aspects of pasturing [73,74]. Our study showed that grazing impacts on greenness became more severe after combining with hydro-climatic factors since 2010. This finding aligns with studies conducted in neighboring regions of China. For instance, vegetation degradation occurred during the implementation of the Household Production Responsibility System policy, resulting in high stocking rates for approximately two decades [75]. Heavy grazing intensity led to decreased soil microbial activities, as well as reduced levels of soil organic carbon and total nitrogen. Additionally, there are increases in soil compaction due to trampling [76,77]. In the eastern part of the country, soil infiltration has been observed in heavily grazed floodplains [34]. Conversely, low grazing intensity improved grassland productivity [78].

Tamir is a medium-sized river in a semi-arid region that experiences significant fluctuations in flow. Despite efforts to legally protect 8.2 million hectares of riparian zones from mining and industrial development in Mongolia [43], it is crucial to implement sustainable grazing management for rivers in drier regions that naturally have functioning floodplains. Based on the recovery of the NDVI after a three-year *dzud* event and studies in similar arid and semi-arid regions, it is recommended to practice moderate grazing intensity in similar plains, especially during low-flow periods. Additionally, measures such as stream bank fencing [79], rotational grazing [80], off-stream watering [81], and rehabilitation of degraded plains should be considered. The increasing number of livestock, projected to

reach 67 million at the national level in 2023, highlights the need for a more comprehensive analysis of floodplain health. This analysis should involve gathering data on changes in plant community structure, groundwater levels, soil structure (compaction), changes in soil microbial activities, soil organic carbon, and nitrogen content and movement. In areas where limited technical capacity and lack of data hinder the implementation of natural resource management, analyzing high-resolution imagery and conducting variance analysis of the NDVI, particularly the mean NDVI among years using the ANOVA Tukey test, can serve as a useful indicator for assessing and monitoring rangelands and maintaining desirable vegetation conditions.

## 5. Conclusions

We analyzed the long-term changes in NDVI in the semi-arid Tamir River plains. The study period includes years with different flow conditions and varying levels of GI. These include a year with relatively high flow and moderate GI in 1991, years with low flow and slight-to-moderate GI in 1997 and 2003, and years with medium flow and moderate-to-extreme GI from 2009 to 2015. In addition, the study period encompasses the most severe major *dzud* events. The results of this study contribute to a better understanding of three key aspects: (1) the influence of hydro-climatic factors on vegetation growth, (2) the impact of grazing pressure on the decline in NDVI, and (3) the resilience of the floodplain meadows in these unregulated and naturally functioning river plains.

Our findings confirm the fact that the hydrological connection and related riparian vegetation are more influenced by local climatic factors and land use than the flow parameters in the medium-sized rivers of arid and semi-arid regions, such as the Tamir River system. This situation has become more pronounced since the mid-1990s, or during low- and medium-flow periods in the target plains and throughout the country, as indicated by other studies. Climate change is reflected in mid-summer heatwaves, the number of rainless days or aridity, increased wind speed, shifts in rain patterns, and seasonal allocations. Additionally, *dzud* events have become more severe when they follow dry summers and occur in subsequent years. Our results support the findings of other research, which state that summer pastures along river valleys, including floodplains, are severely degraded in Mongolia. Medium GI supports vegetation growth during high-flow periods, while low GI is feasible during low-flow periods. Heavy and extreme grazing pressure exacerbates the impacts of climatic risks. Floodplain meadows have a high capacity for recovery, as they are able to recover even during low-flow periods if the GI is managed.

In summary, the transition from a socialist to a market economy in 1991 led to significant changes in livestock management, which, alongside climate warming, has markedly affected NDVI values over the years in the Tamir Rivers plains. Sustainable grazing practices and targeted management strategies are essential to mitigate the adverse effects of climate change and overgrazing on these floodplains. Implementing moderate grazing intensity, rotational grazing, stream bank fencing, and the rehabilitation of degraded plains can help maintain desirable vegetation conditions. Additionally, leveraging high-resolution imagery and NDVI analysis can provide valuable insights for monitoring and managing rangeland health as livestock numbers continue to increase. The dzud disaster of the last winter (2023–2024) caused at least 60% of livestock in some eastern provinces to perish, indicating that animal husbandry in Mongolia is still vulnerable to the climate risks.

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**Data Availability Statement:** The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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## Notes

[1] USGS official website. https://glovis.usgs.gov/app/ (accessed on 25 July 2017).

[2] NASA's Prediction of Worldwide Energy Resources. https://power.larc.nasa.gov/data-access-viewer/ (accessed on 13 December 2022).

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