Supplementary Materials: Variation of Net Primary Production and Its Correlation with Climate Change and Anthropogenic Activities over the Tibetan Plateau *Remote Sensing* 2018, *8*, remotesensing-336096

Zhaohui Luo [1,2], Wenchen Wu [1], Xijun Yu [1,2], Qingmei Song [1], Jian Yang [1], Jiahui Wu [1] and Hengjun Zhang [1,*]

2. Materials and Methods

2.1. Study Area

The Tibetan Plateau (26°00′12″–39°46′50″ N, 73°18′52″–104°46′592″ E), located in Western China (Figure S1) and covering an area of approximately 2.5 million km² is the highest and most extensive highland in the world, with an average elevation exceedings 4 km above sea level, and is called the "Third Pole" of the Earth.

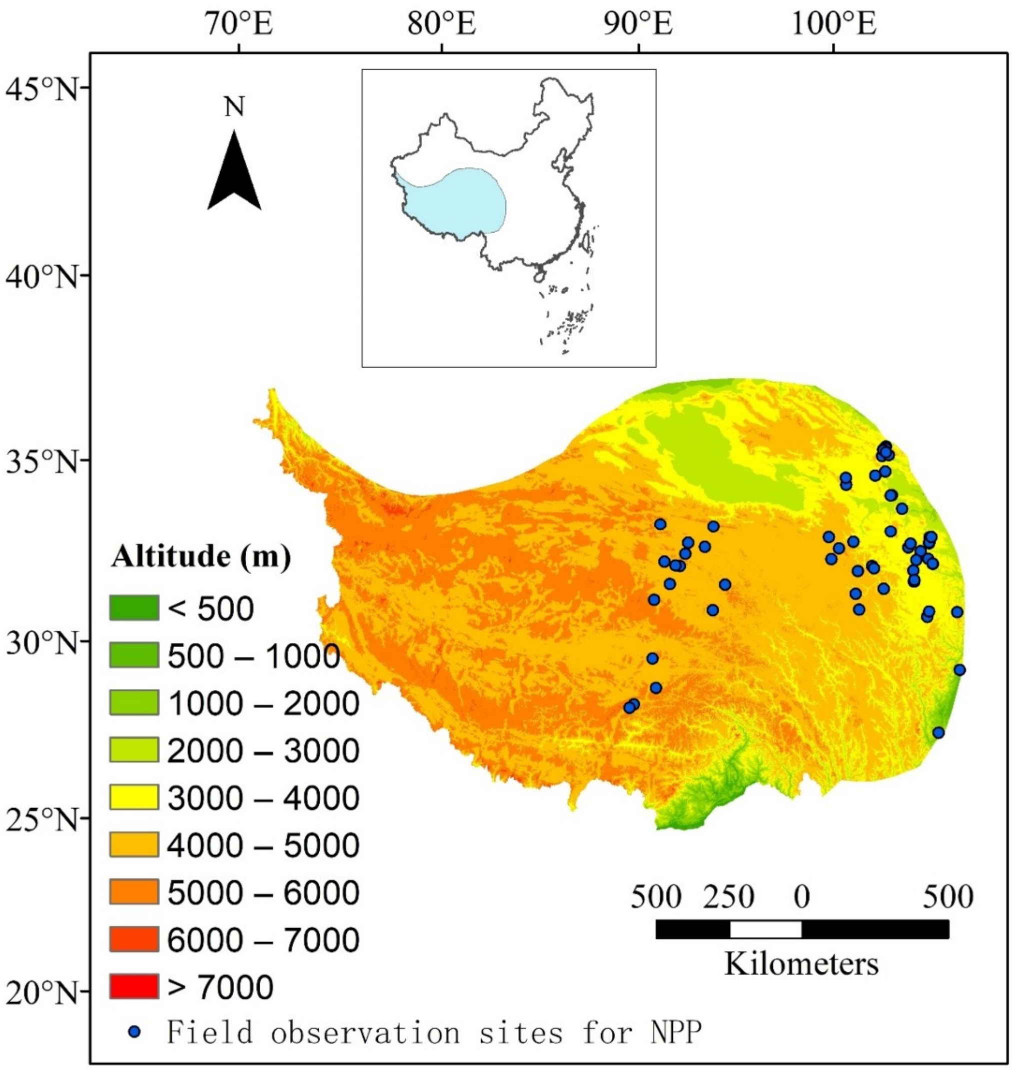

Figure S1. Altitude map for the Tibetan Plateau and also field observation sites for NPP on the plateau.

2.2.3. Land Cover Data

The Global Land Cover 2000 (GLC-2000; Figure S2) dataset was applied to recognize land cover types in the Tibetan Plateau. This dataset, with a spatial resolution of 1 km, was generated by daily S1 data (from the SPOT-4 satellite) based on different classification methods, and local expert knowledge was considered to improve the data accuracy.

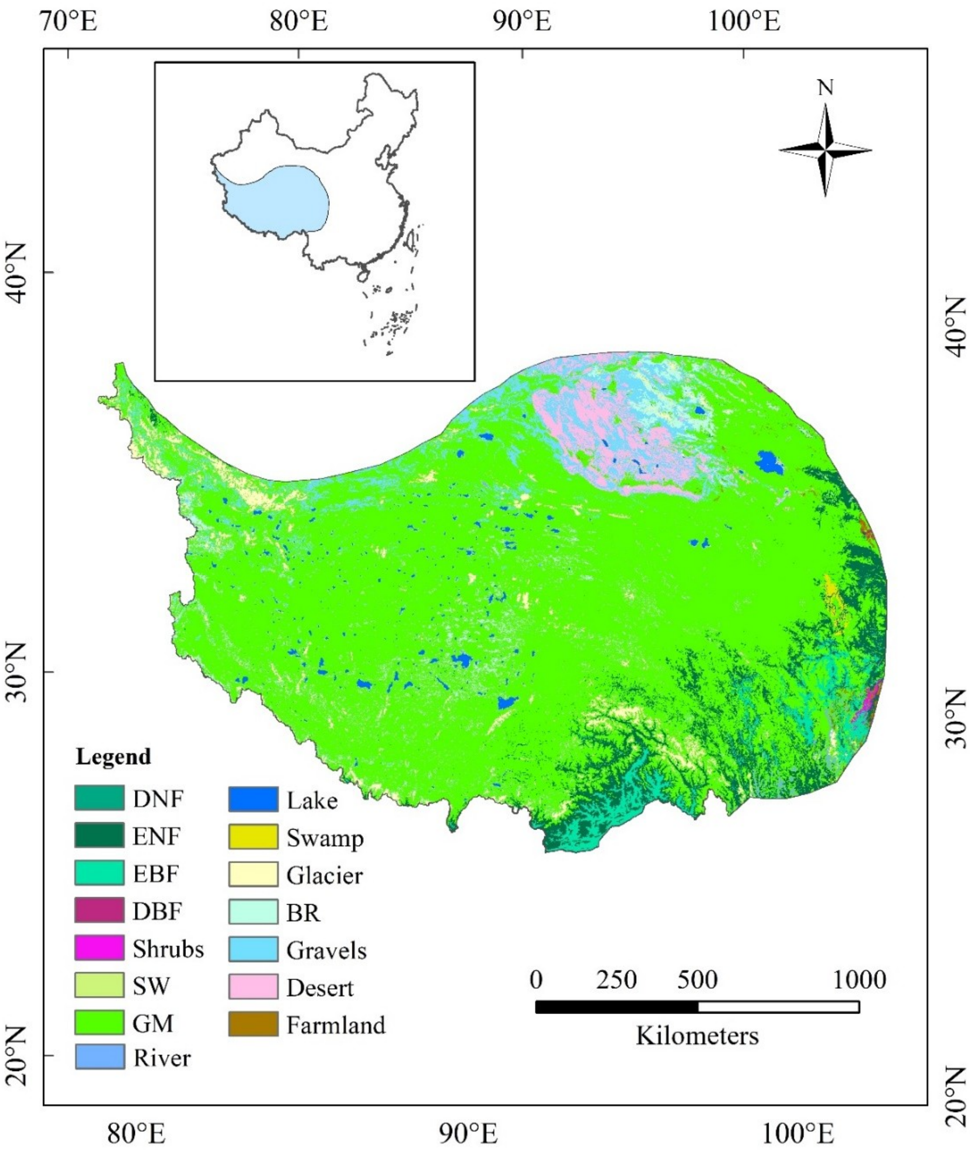

Figure S2. Vegetation types (DNF, deciduous needle-leaf forest; ENF, evergreen needle-leaf forest; EBF, evergreen broadleaf forest; DBF, deciduous broadleaf forest; SW, sparse woods; GM, grassland and meadow; and BR, bare rocks) across the Tibetan Plateau.

2.3.1. NPP Estimation and Validation

After NPP was estimated based on the original and modified CASA models, field-observed biomass data acquired from previously published studies encompassing the time range between 2001 and 2015 (Table S1) were used to evaluate the performance of the models. Similar to previous studies, the biomass was converted to NPP based on Equations (5)–(7).

Table S1. Site information of field NPP data used in this study.

ID	Latitude (°)	Longitude (°)	Year	Reference	ID	Latitude (°)	Longitude (°)	Year	Reference
1	102.6667	29.5000	2012	[1]	40	100.5090	34.3821	2014	[14]
2	90.9167	30.3833	2006	[2]	41	100.5072	34.3831	2014	[14]
3	91.0833	30.4833	2006	[2]	42	102.3100	34.4700	2014	[12]
4	91.9167	30.9833	2006	[2]	43	92.7270	34.4710	2008	[3]
5	103.6667	31.2500	2012	[1]	44	101.8833	35.9667	2006	[21]
6	91.7370	31.8180	2008	[3]	45	92.5500	34.4900	2008	[3]
7	102.5811	32.8331	2014	[4]	46	92.0911	34.5911	2008	[7]
8	103.7706	32.9036	2012	[1]	47	102.0300	34.8500	2014	[12]
9	102.8000	34.4833	2012	[5]	48	99.2000	34.9333	2002	[17]
10	99.9000	33.1667	2006	[6]	49	102.8800	34.9400	2014	[12]
11	94.0794	33.2333	2008	[7]	50	102.1300	34.9500	2014	[12]
12	91.7272	33.4936	2008	[7]	51	93.7322	35.0286	2008	[7]
13	92.9325	34.8264	2010	[8]	52	102.9200	35.0900	2014	[12]
14	101.3000	37.6167	2001	[9]	53	102.9900	35.0900	2014	[12]
15	102.6667	32.9833	2015	[10]	54	99.8000	35.1000	2002	[9]
16	102.8833	34.9167	2006	[11]	55	93.0430	35.1450	2008	[3]
17	102.5100	34.7100	2014	[12]	56	98.8000	35.2667	2002	[17]
18	101.8833	35.9667	2007	[13]	57	94.0630	35.6210	2008	[3]
19	101.4461	36.3596	2014	[14]	58	91.8778	35.6475	2008	[7]
20	99.6167	36.9333	2009	[15]	59	101.8833	35.9667	2005	[13]
21	99.7833	33.6167	2001	[16]	60	101.8833	35.9667	2006	[13]
22	100.9167	33.7167	2002	[17]	61	101.4499	36.3632	2014	[14]
23	102.1633	33.8650	2014	[18]	62	101.4981	36.3641	2014	[14]
24	102.1446	33.8657	2014	[18]	63	101.4581	36.3641	2014	[14]
25	102.1773	33.9113	2014	[18]	64	99.6167	36.7333	2009	[15]
26	102.1758	33.9132	2014	[18]	65	100.8500	36.9500	2007	[22]
27	102.1667	34.1833	2010	[19]	66	101.2833	37.0500	2002	[23]
28	98.8667	34.6333	2002	[9]	67	101.2000	37.4833	2005	[24]
29	92.3380	33.9560	2008	[3]	68	101.4833	37.5000	2004	[25]
30	94.5564	33.9619	2008	[7]	69	101.3667	37.5833	2003	[26]
31	101.3500	35.3333	2004	[20]	70	101.3000	37.6167	2002	[9]
32	99.9167	34.2667	2002	[17]	71	101.3000	37.6167	2003	[9]
33	100.5833	34.3167	2003	[19]	72	101.3000	37.6167	2004	[9]
34	102.9600	34.3300	2014	[12]	73	101.3167	37.6167	2004	[27]
35	102.9700	34.3300	2014	[12]	74	101.2667	37.6500	2004	[27]
36	102.9600	34.3400	2014	[12]	75	101.2500	37.6667	2002	[28]
37	100.5084	34.3798	2014	[14]	76	101.3667	37.7000	2002	[28]
38	100.5086	34.3813	2014	[14]	77	101.3833	37.7500	2003	[29]
39	100.5099	34.3816	2014	[14]					

3. Results

3.2. Spatial Patterns of NPP

Figure 2 illustrate the spatial pattern and standard deviation of NPP over 2001–2015 in the Tibetan Plateau. The mean annual NPP for these 15 years showed an increasing pattern from northwest to southeast (Figure 2a). The lowest values occurred in the west and north of the plateau, with values lower than 0.042 kg·C·m^{-2}. In contrast, the highest values (more than 0.700 kg·C·m^{-2}) were found in the southeast of the plateau. NPP values ranging from 0.250 and 0.700 kg·C·m^{-2} mostly occurred in the east of the plateau. For the remaining areas, NPP values mostly ranged from 0.042 to 0.250 kg·C·m^{-2}, and they were mainly distributed in the middle and southwest of the plateau. Additionally, the spatial pattern of annual NPP for each year (2001–2015) was similar to that of the mean annual NPP (Figure S3). The spatial pattern of the standard deviation (Figure 2b) was similar to that of the mean annual NPP. For most of the study area, the standard deviation was lower than 0.037 kg·C·m^{-2}, accounting for 75.70% (Figure S4). However, higher values were found in the east and southeast of the plateau, with values more than 0.037 kg·C·m^{-2}.

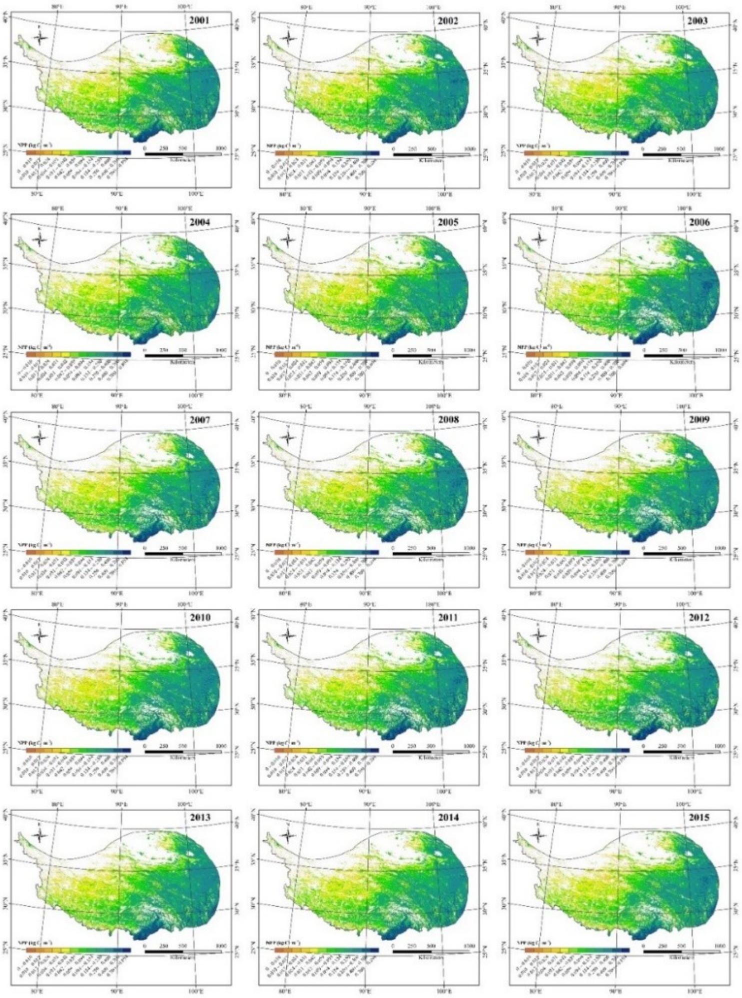

Figure S3. Spatial patterns of annual NPP between 2001 and 2015.

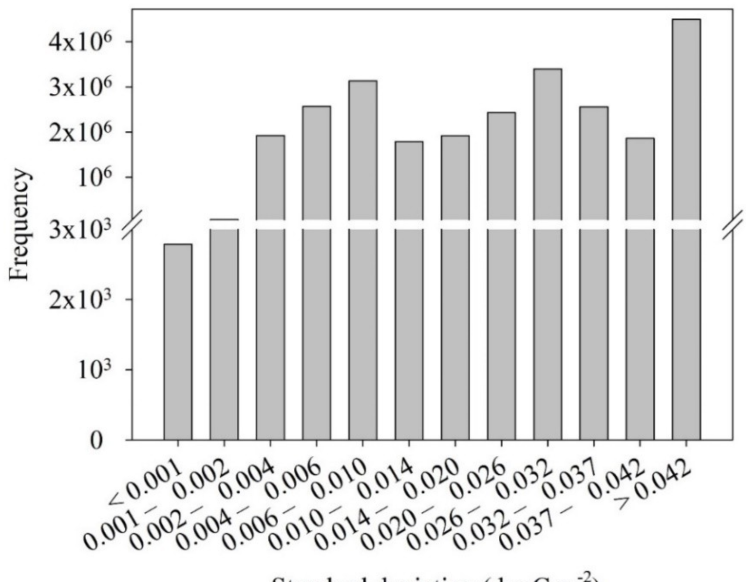

Figure S4. Frequency distributions of NPP standard deviation in the Tibetan Plateau.

3.3. Temporal Trend of NPP

The temporal trend of annual NPP across the Tibetan Plateau is displayed in Figure 3a. During the study period (2001–2015), pixels that displayed either a significant decrease or increase ($p < 0.05$) accounted for 15.01% (Figure 3b). Of the total pixels, 53.20% displayed a decreasing trend, and 9.05% of the total pixels displayed a significantly negative trend ($p < 0.05$; Figure S3). Overall NPP decreased with a mean value of -0.02×10^{-2} kg·C·m^{-2}·a^{-1}, and the magnitudes of decreasing NPP mostly ranged from 0 to -0.15×10^{-2} kg·C·m^{-2}·a^{-1} (Figure S5), distributed in the south and southwest of the Tibetan Plateau. In contrast, 46.80% of the total pixels exhibited an increasing trend, of which approximately 6% showed a significantly positive trend ($p < 0.05$; Figure S5). The increasing trend of NPP was mostly distributed in the center of the plateau, with the magnitudes mainly ranging from 0 to 0.13×10^{-2} kg·C·m^{-2}·a^{-1} (Figure S5).

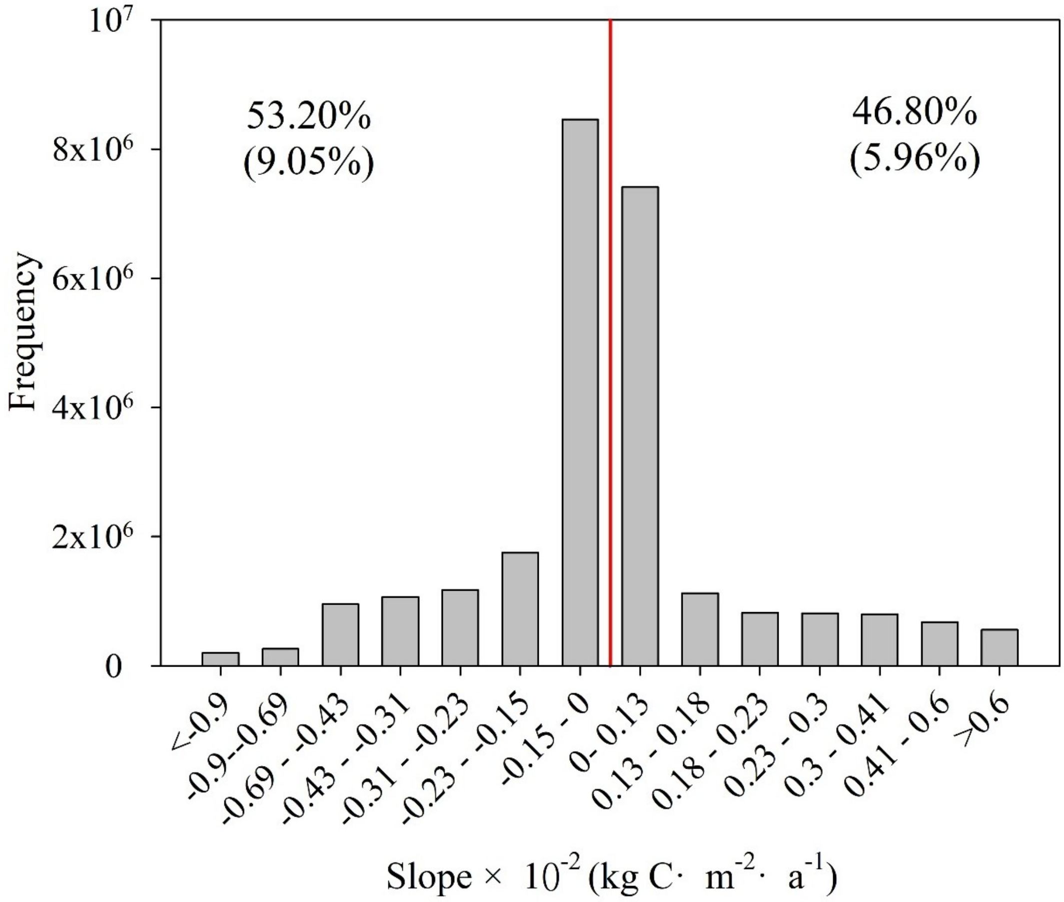

Figure S5. Frequency distributions of NPP trends in the Tibetan Plateau.

3.4.2. Relative Effects of Climatic Factors on NPP

The relative impacts of climate factors on NPP are illustrated in Figure 5. Among the three climate factors, the impact of annual cumulative precipitation was the greatest; Mean annual cumulative precipitation contributed to over 58% of the total pixels, mainly scattered in the middle of the Tibetan Plateau. Annual cumulative solar radiation contributed to approximately 29% of the total pixels, mainly occurring in the eastern edge of the plateau. The extent of the impact of annual mean temperature seemed very limited when compared with the other two climatic factors (<13%), and those pixels were mostly scattered in the southwestern area of the plateau. Furthermore, the annual cumulative precipitation contributed to 47.84% of significantly increasing NPP, followed by the annual solar radiation—approximately 13.48%—and the lowest was the annual mean temperature, only accounting for 13.48%. The percentage of relative contributions of climatic factors to significantly decreasing NPP was similar to that of significantly increasing NPP, approximately

44.58%, 31.98%, and 23.44% for annual cumulative precipitation, annual cumulative solar radiation, and annual mean temperature, respectively (Figure S6).

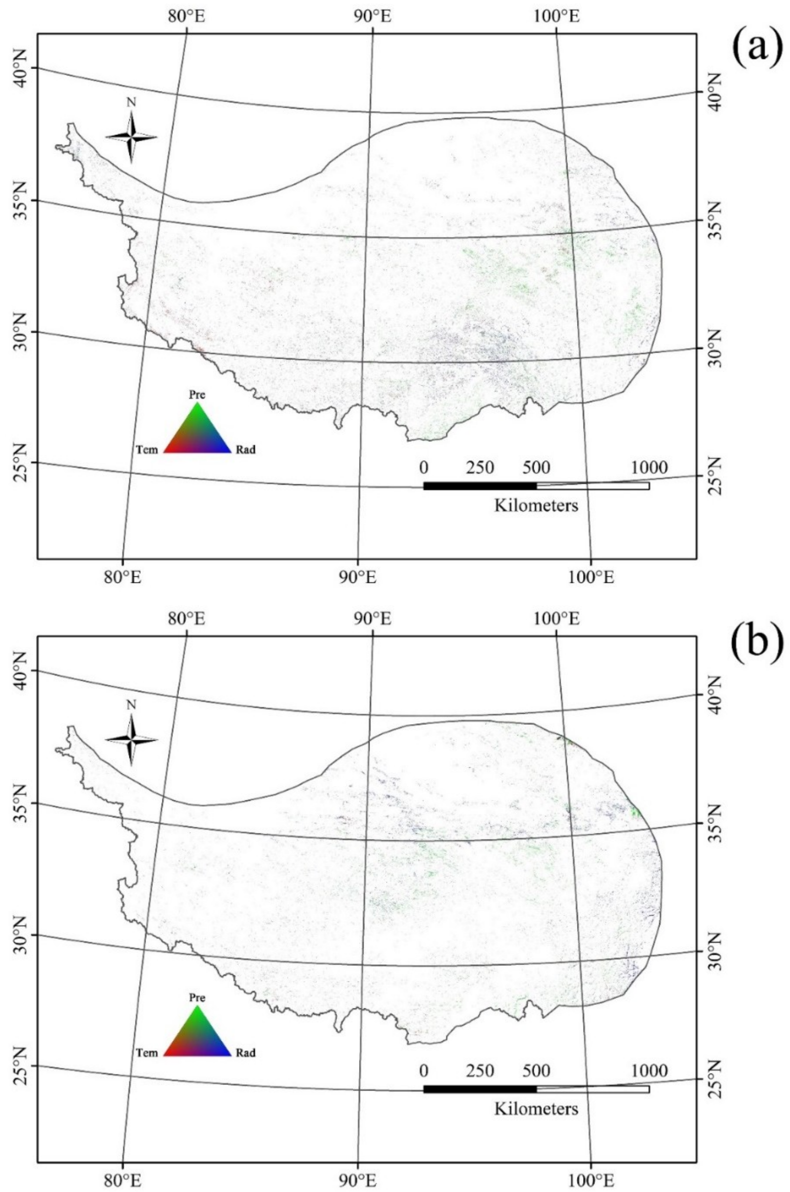

Figure S6. Relative contributions of climate factors on significantly ($p < 0.05$) decreasing NPP (**a**) and significantly increasing NPP (**b**). Only pixels with significantly increasing or decreasing NPP are displayed. Tem, temperature; Pre, precipitation; Rad, solar radiation.

4. Discussion

4.2. Spatiotemporal Variation of NPP

The temporal trend of NPP showed spatial heterogeneity in the Tibetan Plateau, and an overall decreasing trend with a mean value of -0.02×10^{-2} kg·C·m^{-2}·a^{-1} was found, which is similar to previous findings. The reasons for the decreasing NPP include harsh environmental conditions caused by both climate change and anthropogenic activities. For instance, an increasing trend in temperature and a decreasing trend in cumulative precipitation (Figure S7) result in warmer and drier environmental conditions for impending vegetation growth. Additionally, decreased cumulative solar radiation (Figure S7), which inhibits the photosynthesis of vegetation, also contributed to the decreasing NPP.

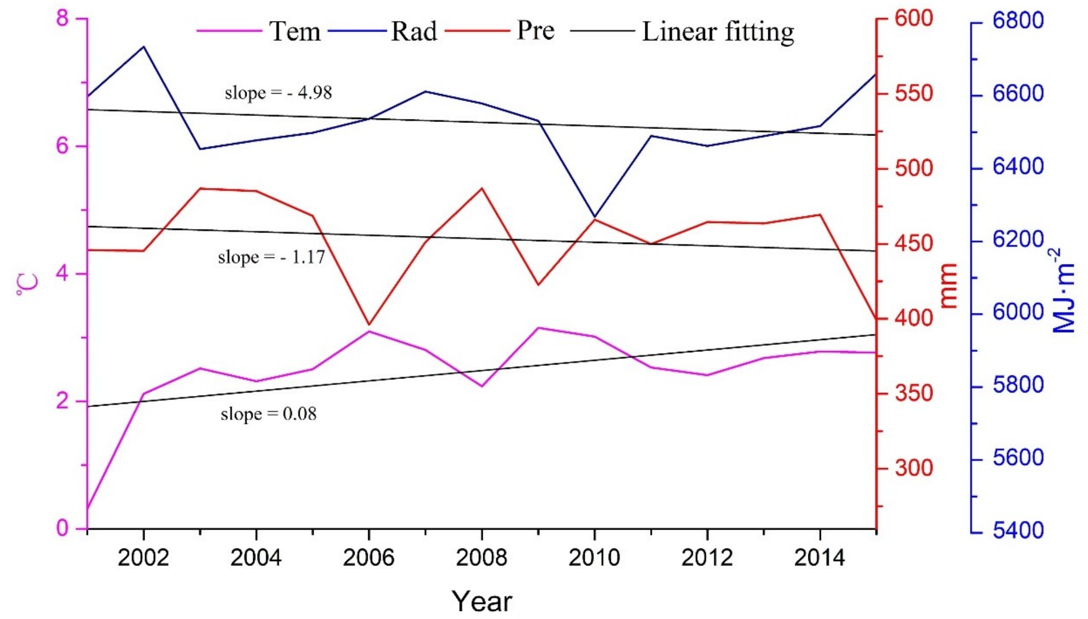

Figure S7. Climatic factors variation in the Tibetan Plateau from 2001 to 2015. Tem, mean annual temperature; Pre, annual cumulative precipitation; Rad, annual cumulative solar radiation.

4.4. Relative Contribution of Climatic Factors and Anthropogenic Activities to NPP

Climate change and anthropogenic activities are the two main factors that affect NPP variation. In terms of climatic factors, approximately 48.57% of the total pixels were regulated by annual cumulative precipitation, and they mainly occurred in the middle of the plateau. This is because precipitation is one of the most important factors affecting vegetation growth in arid and semi-arid areas, especially for grassland with a shallow root system. Additionally, the amount of precipitation in the plateau is usually small and varies extremely in time and space. Moreover, the overall trend of precipitation in the plateau displayed a decreasing trend during the study period (Figure S7 and S8). Both of these reasons make precipitation a dominant climatic factor that regulates vegetation growth in the plateau. The relative contribution of annual cumulative solar radiation accounted for approximately 29% over the study region, and they were mainly distributed in the eastern edge of the plateau. Although solar radiation in the Tibetan Plateau is usually abundant due to less water vapor content, high elevation, and thin clouds, an overall decreasing trend of cumulative solar radiation (Figure S7) may also have contributed to the decreasing trend of NPP in the plateau, as it impacts photosynthesis—such as the composition of chlorophyll and carbohydrate, as well as the decomposition of CO_2—and then impacts dry matter accumulation. The spatial distribution of annual mean temperature that contributed to NPP variation was lower than that of the other two factors, accounting for approximately 12.56% of the total number of pixels. Usually, temperature in the Tibetan Plateau is low due to the high elevation. However, an overall increasing trend of annual mean temperature (Figure S7 and S8) in the plateau may have mitigated the restriction of low temperatures on plant growth.

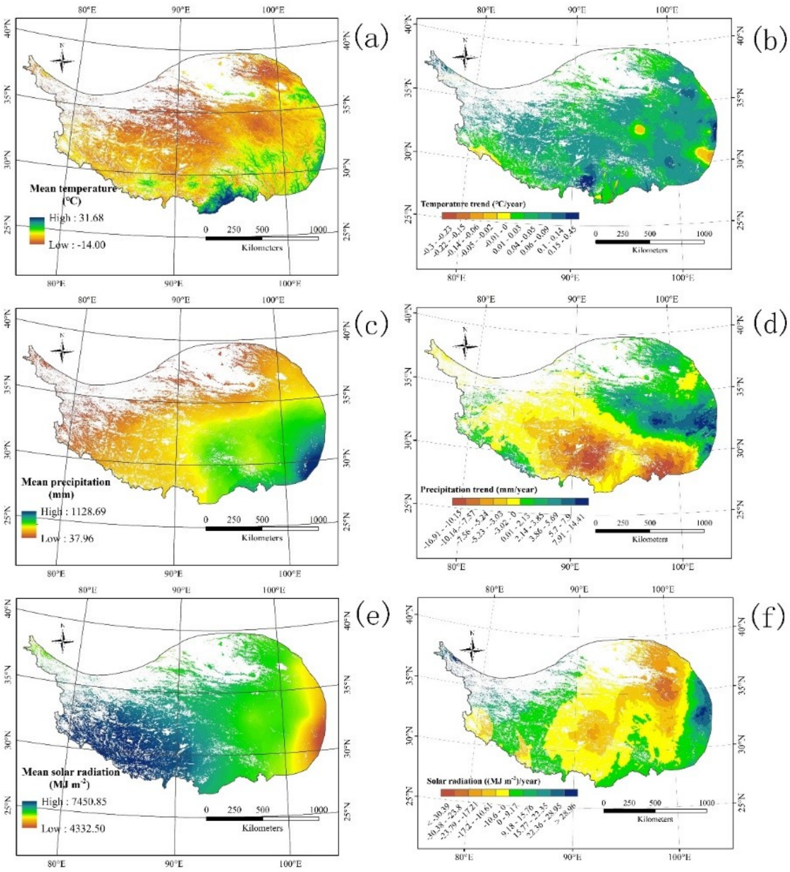

Figure S8 Spatial pattern of mean values of climatic factors and corresponding trends (temperature (**a**, **b**), precipitation (**c**, **d**), and solar radiation (**e**, **f**)) in the Tibetan Plateau between 2001 and 2015.

In terms of human intervention, the effects of ecological destruction on NPP trend changes were larger than that of ecological restoration. For instance, 12.18% of the grassland transformed into built-up areas (Figure S9) in the plateau during 2001–2015, which seems to indicate that ecological destruction is responsible for the decreasing trend of NPP. Therefore, compared with the ecological restoration, such as Natural Forest Conservation Program and Grazing Withdrawal Program, ecological destruction, such as urbanization, unsustainable logging practices, and overgrazing, should be paid more attention in the plateau. Furthermore, more efforts, such as the implementation of grassland protection policies, ecological restoration projects, and ecological compensation in the plateau, should be made in the future to compensate for the negative effects of ecological destruction on decreasing NPP.

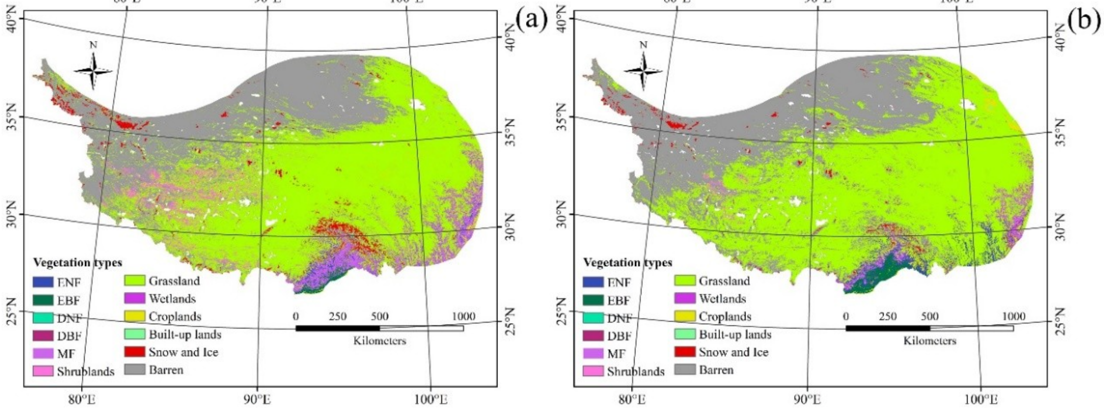

Figure S9 Vegetation types in the Tibetan Plateau in 2001 (**a**) and 2015 (**b**).

References

1. Lv Z.M., Zhou Z.J., Shen L.X., Zhang L. Differences in the biomass of ecological system of wetlands in the eastern margin of the Qinghai-Tibet Plateau. Journal of Sichuan Forestry Science and Technology 2013, 34(6): 22–26.
2. Du X.J. (2007). Research on heterogeneity of Tibet alpine meadow grassland biomass. Master dissertation, Northwest Agriculture and Forestry University, Lanzhou.
3. Chen Y.S., Zhao L., Qin D.H., et al., (2010). A preliminary study of the relationships between alpine grassland biomass and environmental factors in the permafrost regions of the Tibetan Plateau. Journal of Glaciology and Geocryology, 32(2): 405–413.
4. Tserang D.M., Wen Y.L., Ai Y., et al., (2016). Impact of different grazing intensity on soil physical properties and plant biomass in Qinghai-Tibet Plateau alpine meadow ecosystem. Pratacultural Science, 33(10): 1975–1980.
5. Qiu Q., Pan X., Li J.Y., et al., (2014). Comparison on biomass allocation and leaf water use efficiency and $\delta^{13}C$ of 20 shrub seedlings in Tibetan Plateau. Journal of Northwest Forestry University, 2014, 29(4):8–14.
6. Shi D.J., Li X.L., Yang L.J., et al., 2006. Changes and restore countermeasures of different "Black-Soil–Type" degraded grassland. Pratacultural Science, 23(7):1-3.
7. Yang Z.P., Ou Y.H., Song M.H., et al., (2010). Species diversity and above-ground biomass of alpine vegetation in permafrost region of Qinghai-Tibetan Plateau. Chinese Journal of Ecology, 29(4): 617–623.
8. Xu M.H., Liu M., Zhai D.T., et al., (2016). Dynamic changes in biomass and its relationship with environmental factors in an alpine meadow on the Qinghai-Tibetan Plateau， based on simulated warming experiments. Acta Ecologica Sinica, 36(18): 5759–5767.
9. Wang C.T, Wang Q.J, Long R.J, et al., 2004. Changes in plant species diversity and productivity along an elevation gradient in an Alpine meadow. Acta Bot Boreal-Occident Sin, 28(2):240–245.
10. Chen W.N., Chen F.J. 2017. Responses of biomass and species diversity to nitrogen addition in alpine meadows. Pratacultural Science, 34(5):1082–1089.
11. Wang X.F (2008). The impacts of shading, fertilization and cutting on growth of three grasses in Qinghai-Tibet Plateau. Master dissertation, Lanzhou University, Lanzhou.
12. Ma X.B. (2015) Study on the response of the biomass of *Gentianae* on the eastern of Qinghai-Tibetan Plateau to the altitude and environmental factors. Master dissertation, Lanzhou University, Lanzhou.
13. Zhao B.B. (2008). Grazing effects on above-ground biomass allocation of component species and community structure in an alpine meadow plant community. Master dissertation, Lanzhou University, Lanzhou.
14. Liu Z., Li Q., Chen D.D., et al., (2015). Patterns of plant species diversity along an altitudinal gradient and its effect on above-ground biomass in alpine meadows in Qinghai-Tibet Plateau. Biodiversity Science, 23(4):451–462.
15. Wu Y.P., Chen K.L., Zhang F., et al., (2011). Relationship between species diversity and above-ground biomass of inland alpine wetlands of Qinghai Lake. Bulletin of Soil and Water Conservation, 31(1): 76–80.
16. Dong Q.M., Zhao X.Q., Ma Y.S., et al., (2005). Regressive analysis between stocking rate for yak and aboveground and underground biomass of warm-season pasture in *Kobrecia parva* alpine meadow. Pratacultural Science, 22(5): 65–71.
17. Wang C.T., Wang Q.J., Long R.J., et al., (2004). Changes in plant species diversity and productivity along an elevation gradient in an alpine meadow. Acta Phytoecologica Sinica, 28 (2):240–245.
18. Luo Y.Y, Meng Q.T, Zhang J.H, et al., (2014). Species diversity and biomass in relation to soil properties of alpine meadows in the eastern Tibetan Plateau in different degradation stages. ournal of Glaciology and Geocryology, 36(5):1298–1305.
19. Zhao Z., Zhao Y., Rong L.Y. (2016). Effects of fire disaster on production and vegetation community of sub-alpine meadow in Qinghai-Tibet Plateau. Grassland and Turf, 36(2):82–86.

20. Wang X.L., Gan Y.M., Zhang L., et al. (2006). Study on underground photomass of heavily degraded Kobresiam capallif olia grassland in Qinghai Lake area. Sichuan Cao yuan, 6:6–9.
21. Zhao B.B., Niu K.C., Du G.Z. (2009). The effect of grazing on above-ground biomass allocation of 27 plant species in an alpine meadow plant community in Qinghai-Tibetan Plateau. Acta Ecologica Sinica, 29(3):1956–1605.
22. Zhu B.W., Zhou H.K., Xu Y.X., et al., (2008). Study on seasonal dynamics of biomass in meadow grassland of north shore of Qinghai Lake. Pratacultural Science, 25(12): 62–66.
23. Zhou H.K., Zhou L., Zhao X.Q., et al., (2002). Study of formation pattern of below-ground biomass in *Potentilla fruticosa* shrub. Acta Prataculturae Sinica, 11(2): 59–65.
24. Shi H.L., Wang Q.J., Jing Z.C., et al., (2005). The structure, biodiversity and stability of artificial grassland plant communities in the source regions of the Yangze and Yellow River, Acta Prataculturae Sinica, 14(3): 23–30.
25. Zhao Y.N., Zhao L., Wang Q.X., et al., (2006). Estimation of Biomass and Annual Turnover Quantities of *Potentilla Froticosa* Shrub. Acta Agrestia Sinica, 14(1): 72–76.
26. Liu W., Zhou H.K., Zhou L. (2005). Biomass distribution pattern of degraded grassland in Alpine meadow. Grassland of China, 27(2): 9–15.
27. Wang Q.J., Shi H.L., Jing Zeng C., et al., (2004). Recovery and benefit analysis of ecology on degraded natural grassland of the source region of yangze and yellow rivers, Pratacultural Science, 21(12):37–41.
28. Li Y.N., Wang Q.X., Gu S., et al., (2004). Integrated monitoring of alpine vegetation types and its primary production. Acta Geographica Sinica, 59(1):40–48.
29. Wang C.T., Wang Q.J., Shen A.X., et al., (2003). Response of biodiversity and productivity to simulated rainfall on an alpine Kobresia humilis meadow. Acta Bot. Boreal-Occident. Sin, 23(10):1713–1718.