**Supporting Methods**

*Normalized Difference Vegetation Index*

To determine the effects of drought on vegetation greenness, we followed the same procedure as we did for the gross primary productivity/carbon (C) uptake data (see main text) using the MODIS 16-day (averaged) Normalized Difference Vegetation Index (NDVI) MYD13Q1 data product (2003-2020). NDVI is a commonly used metric of vegetation activity and density describing ‘greenness’ that is also a key input variable to produce the C uptake estimates (Robinson et al., 2018; Running et al., 2004). NDVI is derived from the spectral reflectance signals of the red and near infra-red spectrum and, for the purposes of studying vegetation, takes on (unitless) values between 0 (no vegetation) and 1 (high vegetation density). We analyzed NDVI in addition to C uptake because the MODIS-based gross primary productivity product is generated using NDVI and climate parameters including daily temperature and vapor pressure deficit (Robinson et al., 2018; Running et al., 2004). NDVI provides the spectral index used to estimate the fraction of absorbed photosynthetically active radiation for the MOD17 algorithm. Climate parameters provide biome-specific bounds on C uptake; freezing temperatures or high vapor pressure deficit swill induce stomatal closure. Thus, MODIS-based carbon uptake is a modeled output, whereas NDVI or other greenness measure are a single and more direct proxy that has also been shown to capture temporal productivity dynamics within grasslands (Hufkens et al., 2016). The NDVI data product also does not require the input of weather variables and is purely derived from reflectance signals. Therefore, NDVI provided an independent metric to assess and compare drought impacts to carbon uptake and to relate drought impacts to weather variables.

*Analysis of seasonal weather variables*

Given the connection between vapor pressure deficit (VPD), temperature (Lawrence, 2005), and to a lesser extent precipitation, we first assessed multicollinearity among the variables. We first correlated the changes (absolute deviations from their mean values) in these three weather variables in summer during drought, both among each other and with peak reductions in NDVI (**Table S7**). Not surprisingly, this showed strong evidence for collinearity between changes in summer temperature and VPD (Spearman’sρ = 0.88). We subsequently assessed the variance inflation factor (VIF) when using these two as main effects in a model predicting maximum reductions in NDVI (VIF = 5.2). We chose to move forward with VPD because this was more strongly correlated with peak reductions in NDVI (**Table S7**). Changes in summer VPD were also correlated with changes in precipitation during drought (ρ = -0.67); however, this did not translate to high VIF when including both as main effects in a model predicting peak reductions in NDVI (VIF = 1.8).

Therefore, we focused our analysis of spatial variation in peak NDVI reductions during drought on absolute changes in precipitation and VPD during the summer months. However, our analysis of VPD limits our ability to distinguish between temperature, vapor pressure, or both as drivers of a relationship with NDVI. A follow-up analysis using changes in spring precipitation and VPD explained less variance in peak reductions in NDVI; neither model explained more than 16% of the spatial variation in peak NDVI reductions, further supporting the use of summer weather variables to predict peak NDVI reductions.

**References**

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Robinson, N. P., Allred, B. W., Smith, W. K., Jones, M. O., Moreno, A., Erickson, T. A., Naugle, D. E., & Running, S. W. (2018). Terrestrial primary production for the conterminous United States derived from Landsat 30 m and MODIS 250 m. *Remote Sensing in Ecology and Conservation*, *4*(3), 264–280. https://doi.org/10.1002/rse2.74

Running, S. W., Nemani, R. R., Heinsch, F. A., Zhao, M., Reeves, M., & Hashimoto, H. (2004). A Continuous Satellite-Derived Measure of Global Terrestrial Primary Production. *BioScience*, *54*(6), 547. https://doi.org/10.1641/0006-3568(2004)054[0547:ACSMOG]2.0.CO;2

**Supporting Results**

*Seasonality of temperature, precipitation, and vapor pressure deficit*

Median percent reductions in precipitation were greater during spring (-71.9%) than summer (-60.5%) across the shortgrass steppe, although this reversed for absolute changes (**Tables S4 & S5**). Absolute and relative reductions were consistently smaller during spring (-49.3%) than summer (-59%) across the northern mixed prairies. Thus, absolute (mm) reductions in precipitation tended to be greater during the summer. Yet, the change in the percent of spring precipitation­ during drought was inconsistent across both ecoregions and exhibited no clear directionality (**Figure S12**). We observed small, but significant, *decreases* in the percent of spring precipitation during drought in the shortgrass steppe (median = -7%, bootstrapped T = -3.9 ± 0.1) but *increases* in the northern mixed prairies (median = 6%, bootstrapped T = 4.5 ± 0.9).

Median absolute temperature increases across the shortgrass steppe were twice as large during summer (2.1 °C) than spring (1.1 °C), whereas median temperature increases across the northern mixed prairies was ~1.3 °C in spring and summer, which translated to a far greater percent increase in temperatures during the spring (**Tables S4 & S5**). Vapor pressure deficit was most consistent in changing between spring and summer; the absolute increase in the average maximum vapor pressure deficit was over twice as large during summer (1.1 kPa) as compared to spring (0.5 kPa) across the shortgrass steppe and over three times as large (0.7 vs. 0.2 kPa) across the northern mixed prairies (**Tables S4 & S5**). Thus, absolute increases in vapor pressure deficit during drought were consistently greater during the summer than spring.

**Supporting tables**

**Table S1.** Percentiles (25th, 50th, and 75th) of drought impacts to growing season temperature and precipitation for each ecoregion.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Ecoregion |  | Absolute change | | | % Change | | |
|  |  | *50th* | *25th* | *75th* | *50th* | *25th* | *75th* |
| Shortgrass steppe | Precipitation (mm) | -215.4 | -287.2 | -177 | -57.4 | -68.1 | -49.3 |
| Temperature (oC) | 1.4 | 1.1 | 1.8 | 8 | 6.1 | 9.7 |
| Northern mixed prairies | Precipitation (mm) | -217.1 | -189.8 | -165 | -48.8 | -58.2 | -41.9 |
| Temperature (oC) | 1 | 0.6 | 1.8 | 8 | 4.8 | 13.6 |

**Table S2.** Percentiles (25th, 50th, and 75th) of absolute maximum and total reductions in carbon uptake resulting from drought for each ecoregion.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Ecoregion | Maximum reduction (g C m-2 16-days-1) | | | Total reduction (g C m-2) | | |
|  | *50th* | *25th* | *75th* | *50th* | *25th* | *75th* |
| Shortgrass steppe | -22.1 | -28.4 | -16.6 | -142.8 | -189.7 | -99.6 |
| Northern mixed prairies | -25.6 | -36.9 | -15.8 | -71.9 | -144.9 | -22.8 |

**Table S3.** Percentiles (25th, 50th, and 75th) of drought impacts to day by which 25%, 50%, and 75% of total C uptake occurs for each ecoregion. Negative values indicate this day occurred earlier during drought.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Ecoregion | 25% of total (number of days) | | | 50% of total (number of days) | | | 75% of total (number of days) | | |
|  | *50th* | *25th* | *75th* | *50th* | *25th* | *75th* | *50th* | *25th* | *75th* |
| Shortgrass steppe | -21 | -25 | -14 | -22 | -32 | -8 | 3 | -6 | 12 |
| Northern mixed prairies | -15 | -18 | -8 | -12 | -16 | -6 | -4 | -9 | 1 |

**Table S4.** Percentiles (25th, 50th, and 75th) of absolute changes to spring versus summer temperature, precipitation, and vapor pressure deficit during drought for each ecoregion.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Ecoregion |  | Spring | | | Summer | | |
|  |  | *50th* | *25th* | *75th* | *50th* | *25th* | *75th* |
| Shortgrass steppe | Precipitation (mm) | -79.9 | -106.3 | -60.4 | -112.5 | -140.3 | -87.1 |
| Temperature (oC) | 1.1 | 0.4 | 2.3 | 2.1 | 1.6 | 2.8 |
| VPD (kPa) | 0.5 | 0.4 | 0.6 | 1.1 | 0.8 | 1.4 |
| Northern mixed prairies | Precipitation (mm) | -75.3 | -94.7 | -52.4 | -85.6 | -117.4 | -58.9 |
| Temperature (oC) | 1.3 | 0.85 | 2.9 | 1.4 | 1 | 1.9 |
| VPD (kPa) | 0.2 | 0.1 | 0.5 | 0.7 | 0.5 | 0.9 |

**Table S5.** Percentiles (25th, 50th, and 75th) of percent changes to spring versus summer temperature, precipitation, and vapor pressure deficit during drought for each ecoregion.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Ecoregion |  | Spring | | | Summer | | |
|  |  | *50th* | *25th* | *75th* | *50th* | *25th* | *75th* |
| Shortgrass steppe | Precipitation (mm) | -71.9 | -88 | -50.6 | -60.5 | -72.8 | -48.1 |
| Temperature (oC) | 8.2 | 3.4 | 23.4 | 9.7 | 7.1 | 11.3 |
| VPD (kPa) | 25 | 18 | 32 | 32 | 25 | 40 |
| Northern mixed prairies | Precipitation (mm) | -49.3 | -63.1 | -32.1 | -59 | -74.4 | -42.2 |
| Temperature (oC) | 22.9 | 13.3 | 41.5 | 7.2 | 5 | 9 |
| VPD (kPa) | 16 | 8 | 40 | 24 | 18 | 32.5 |

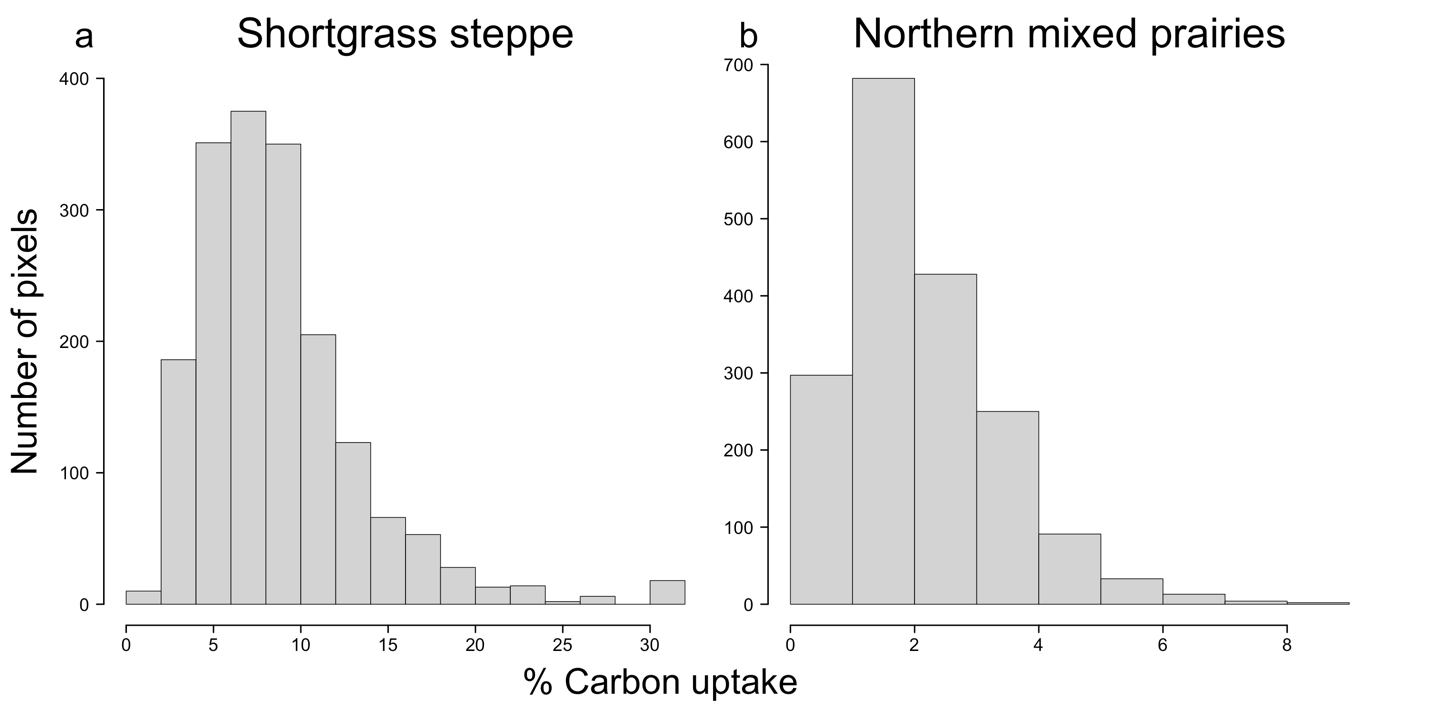
**Table S6.** Model summaries (using multiple regression) of the effect of changes (absolute deviation from mean) in summer precipitation or vapor pressure deficit on peak (absolute) reductions in NDVI (unitless). Models include both the main effects of weather and ecoregion, as well as their interaction (see methods).

|  |  |  |  |
| --- | --- | --- | --- |
| **Change in Summer Precipitation (mm)** | | | |
| *Predictors* | *Estimates* | *CI* | *p* |
| Intercept | -0.055 | -0.067 – -0.044 | **<0.001** |
| change in summer precip | 0.0008 | 0.0007 – 0.0009 | **<0.001** |
|  |
| ecoregion [shortgrass\_steppe] | -0.031 | -0.050 – -0.012 | **0.002** |  |
|  |
| change in summer precip [shortgrass\_steppe] | -0.0004 | -0.0006 – -0.0002 | **<0.001** |  |
|  |
|  |
| Observations | 719 |  |  |  |
| R2 adjusted | 0.29 |  |  |  |
| **Change in Summer VPD (kPa)** | | | |  |
| *Predictors* | *Estimates* | *CI* | *p* |  |
| Intercept | -0.04 | -0.05 – -0.03 | **<0.001** |  |
| change in summer VPD | -0.13 | -0.14 – -0.12 | **<0.001** |  |
| ecoregion [shortgrass\_steppe] | -0.03 | -0.05 – -0.02 | **<0.001** |  |
|  |
| change in summer VPD [shortgrass\_steppe] | 0.08 | 0.06 – 0.09 | **<0.001** |  |
|  |
|  |
| Observations | 719 |  |  |  |
| R2 adjusted | 0.39 |  |  |  |

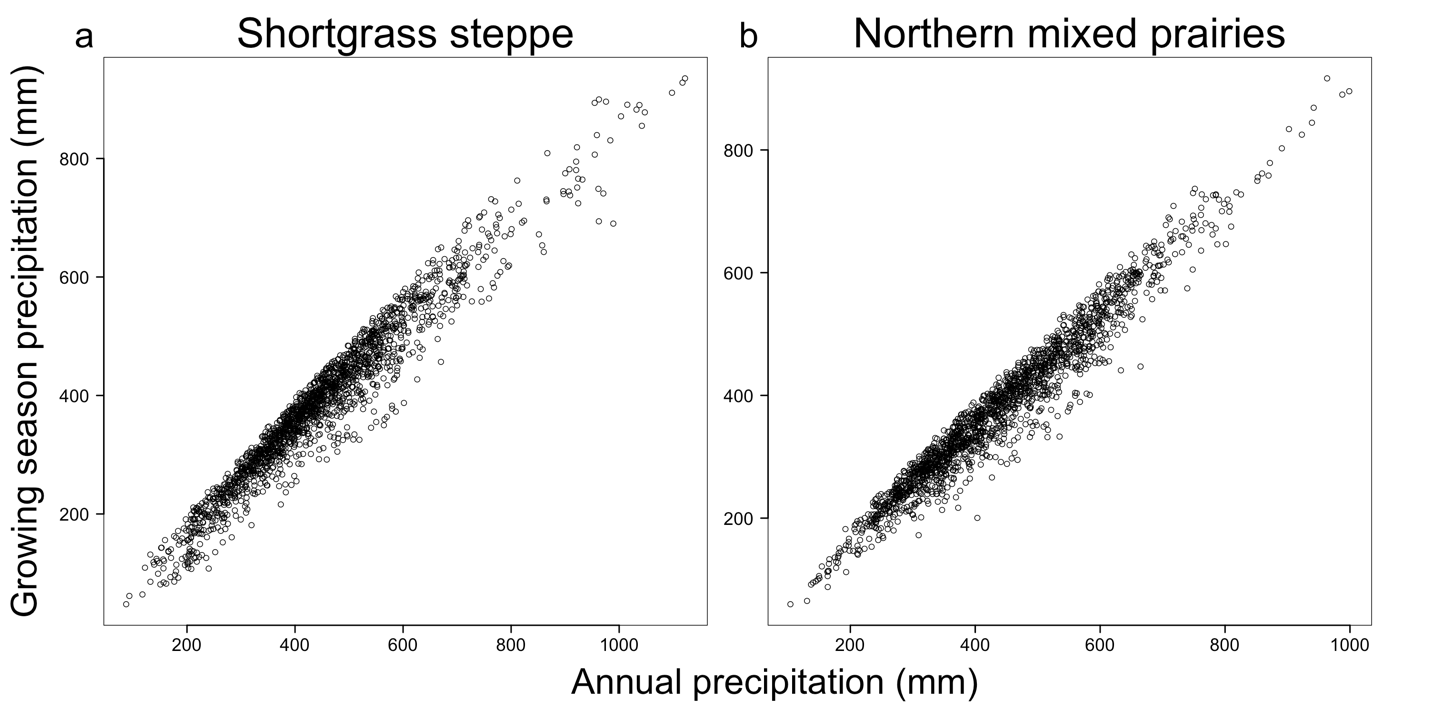
**Table S7.** Correlations (Spearman’s ρ) between and among 1) peak reductions in NDVI, and 2) absolute changes (deviations from mean) in summer vapor pressure deficit (VPD), temperature, and precipitation.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Peak NDVI Reduction | Change in Summer VPD | Change in Summer Temp | Change in Summer Precip |
| Peak NDVI Reduction | 1 | -0.6 | -0.53 | 0.49 |
| Change in Summer VPD | -0.6 | 1 | 0.88 | -0.67 |
| Change in Summer Temp | -0.53 | 0.88 | 1 | -0.49 |
| Change in Summer Precip | 0.49 | -0.67 | -0.49 | 1 |

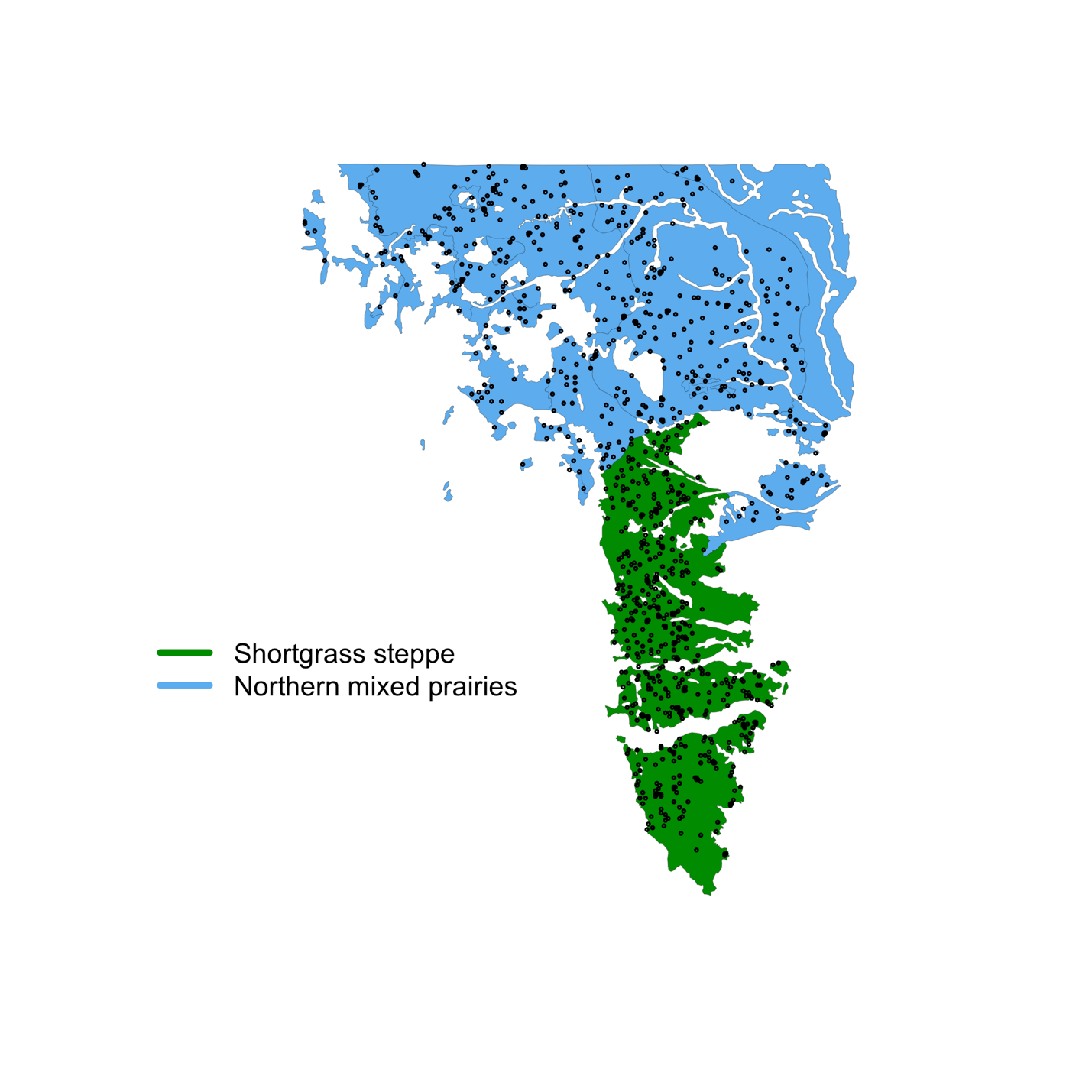
**Supporting figures**



**Figure S1.** Histograms of the average percent of total annual carbon uptake that occurred in (non-growing season) months not included in the analyses for each ecoregion.

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**Figure S2.** Correlation between growing season precipitation and annual precipitation. Growing season precipitation was defined here as total precipitation occurring between 26 February and 24 October for each ecoregion.

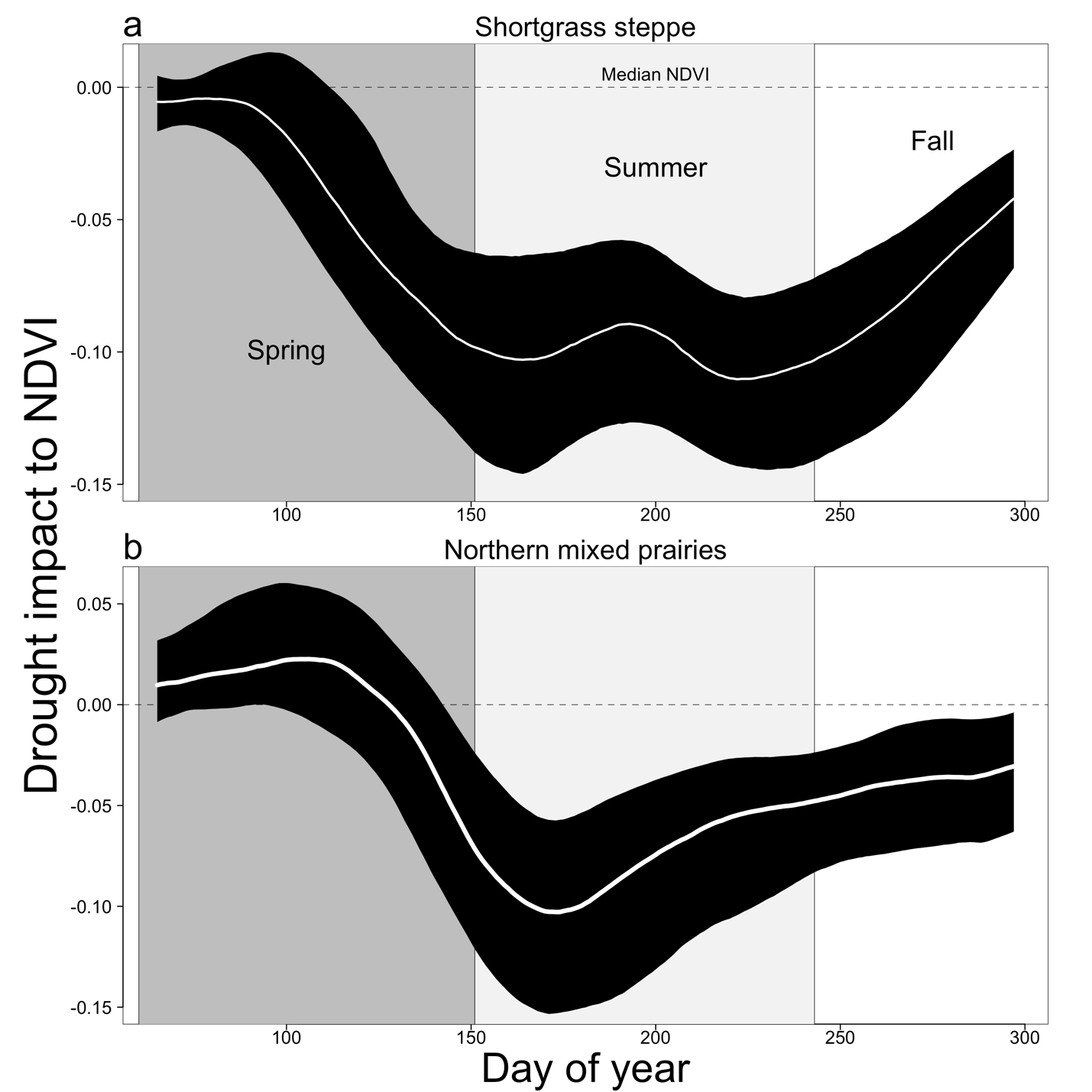


**Figure S3.** Pixel locations used from a stratified subset of all data for vapor pressure deficit analyses.

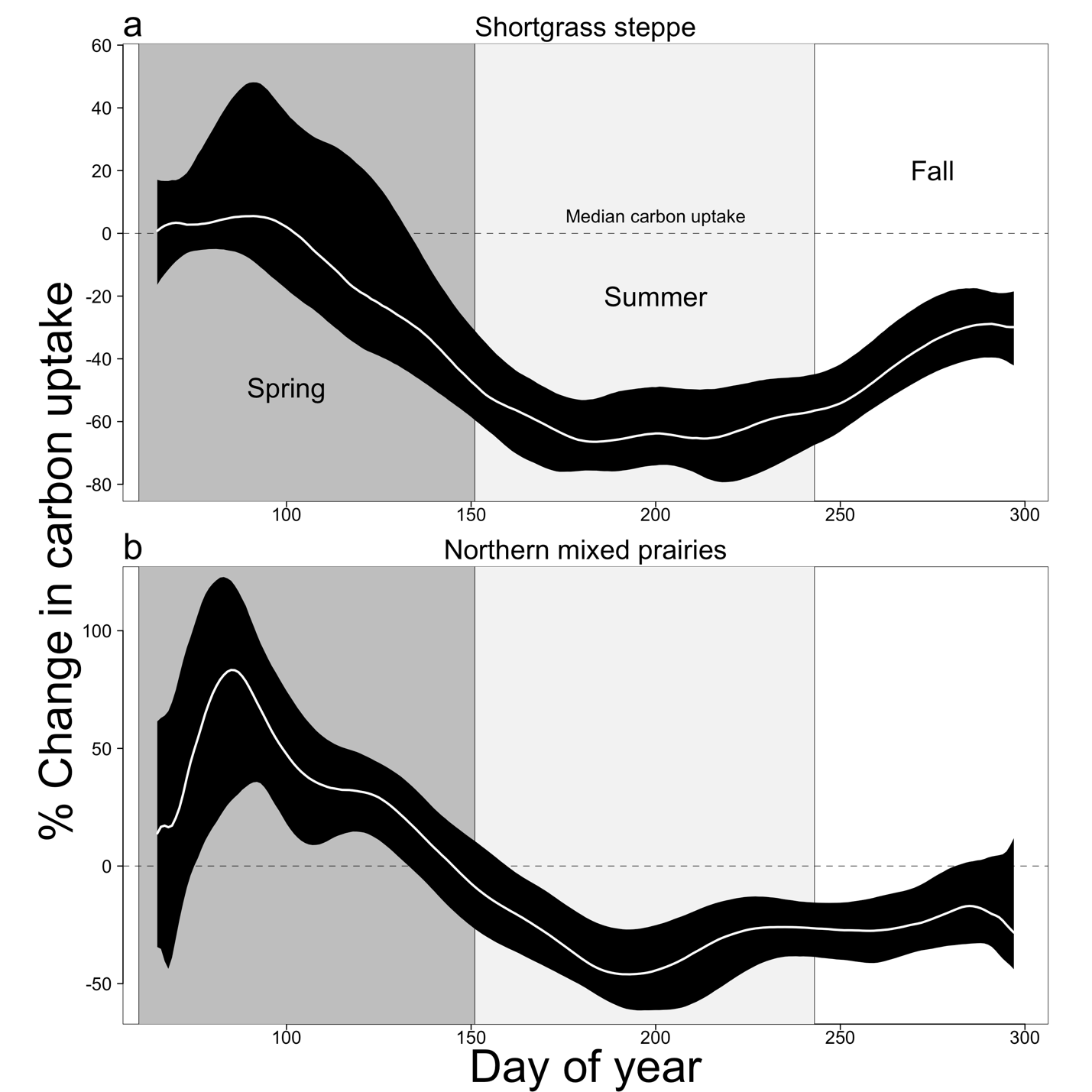
**Diagram

Description automatically generated with medium confidence**

**Figure S4.** Drought impacts to carbon uptake during extreme drought in each ecoregion for the 1 km resolution subset of sites. The white line depicts the median change whereas the shading indicates the interquartile range.

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**Figure S5.** Impacts to the Normalized Difference Vegetation Index (NDVI, a unitless metric of vegetation greenness) during drought in each ecoregion.The white line depicts the median change whereas the shading indicates the interquartile range.

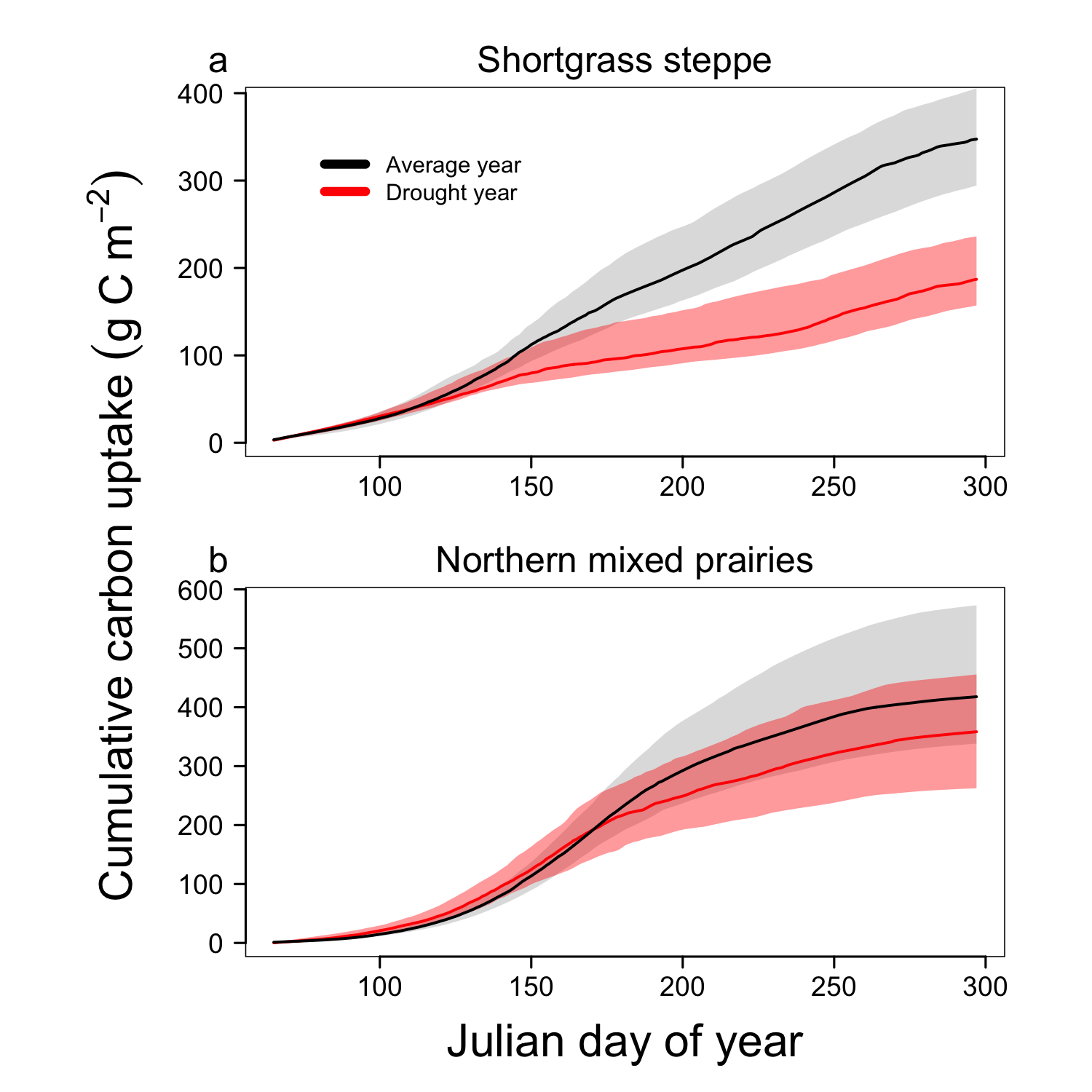


**Figure S6.** Percent changes to 16-day total carbon uptake during drought in each ecoregion. The white line depicts the median change whereas the shading indicates the interquartile range.

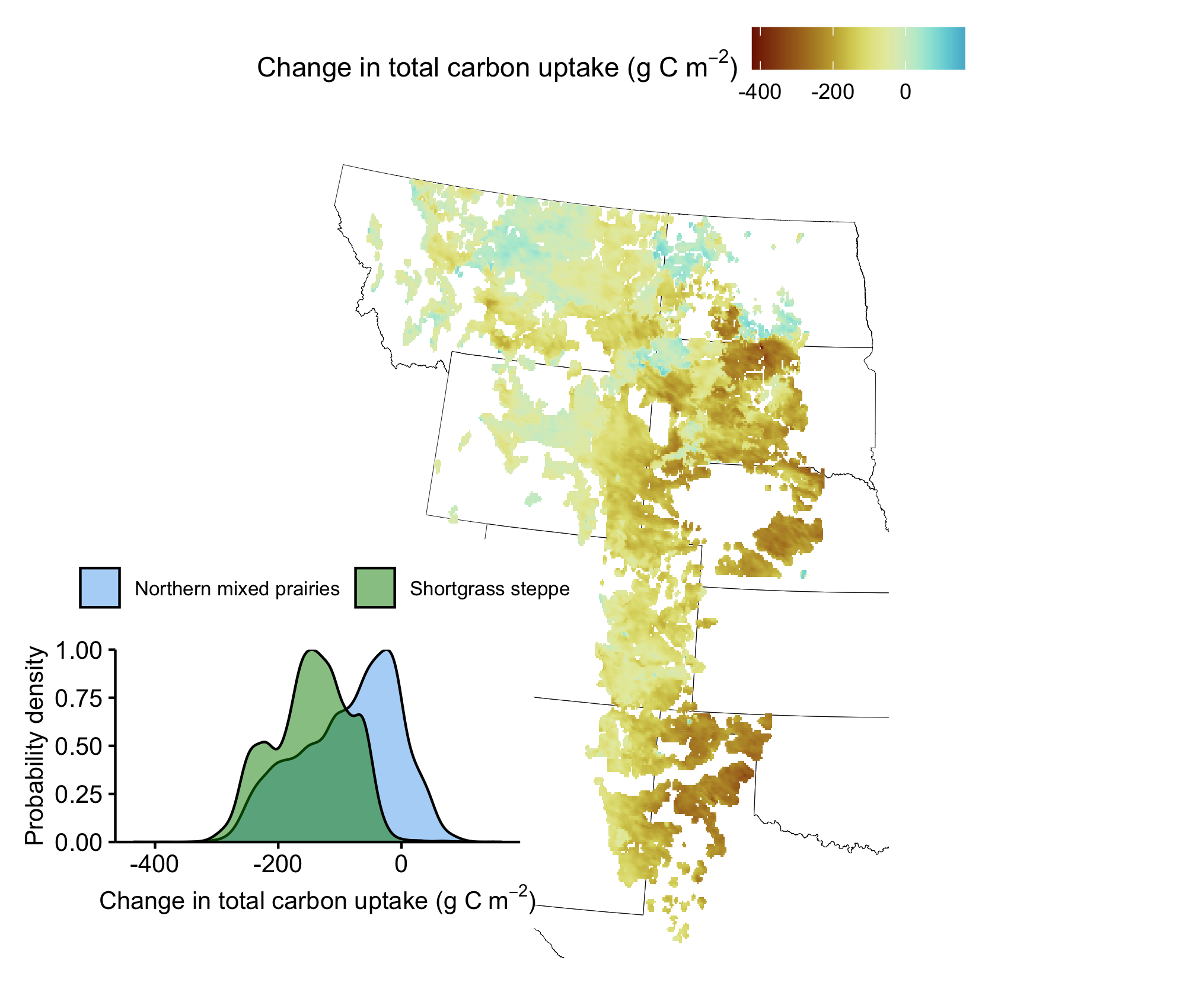
**A picture containing map

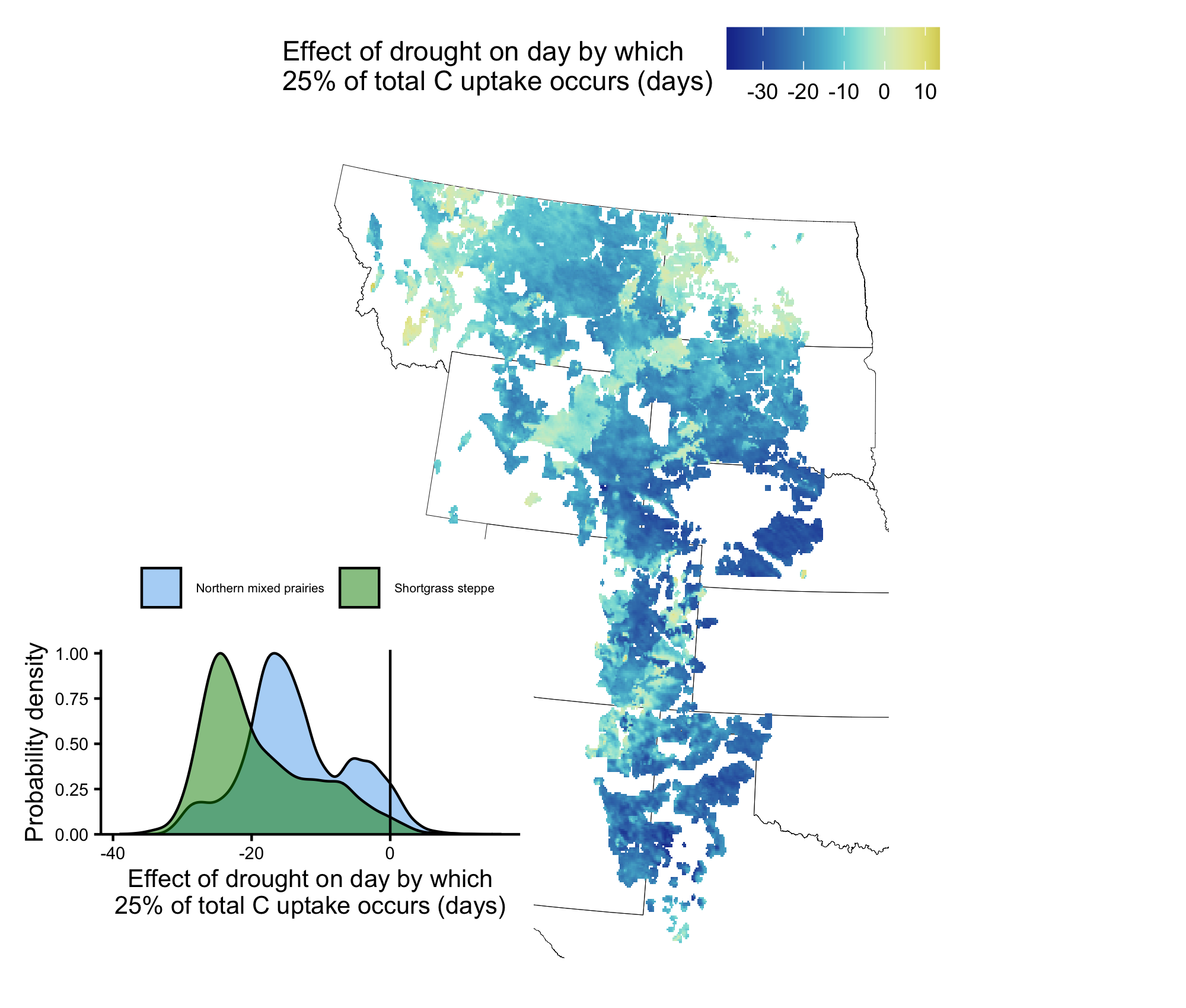
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**Figure S7.** Absolute (g C m-2 16-days-1) and relative (%) maximum reductions in carbon uptake during drought. Panel a) depicts spatial variation in the absolute maximum reduction in 16-day carbon uptake, while panel b) translates this to relative (% change from median) impacts. Panels c) and d) show the probability density functions (scaled to 1) of these impacts for each ecoregion.

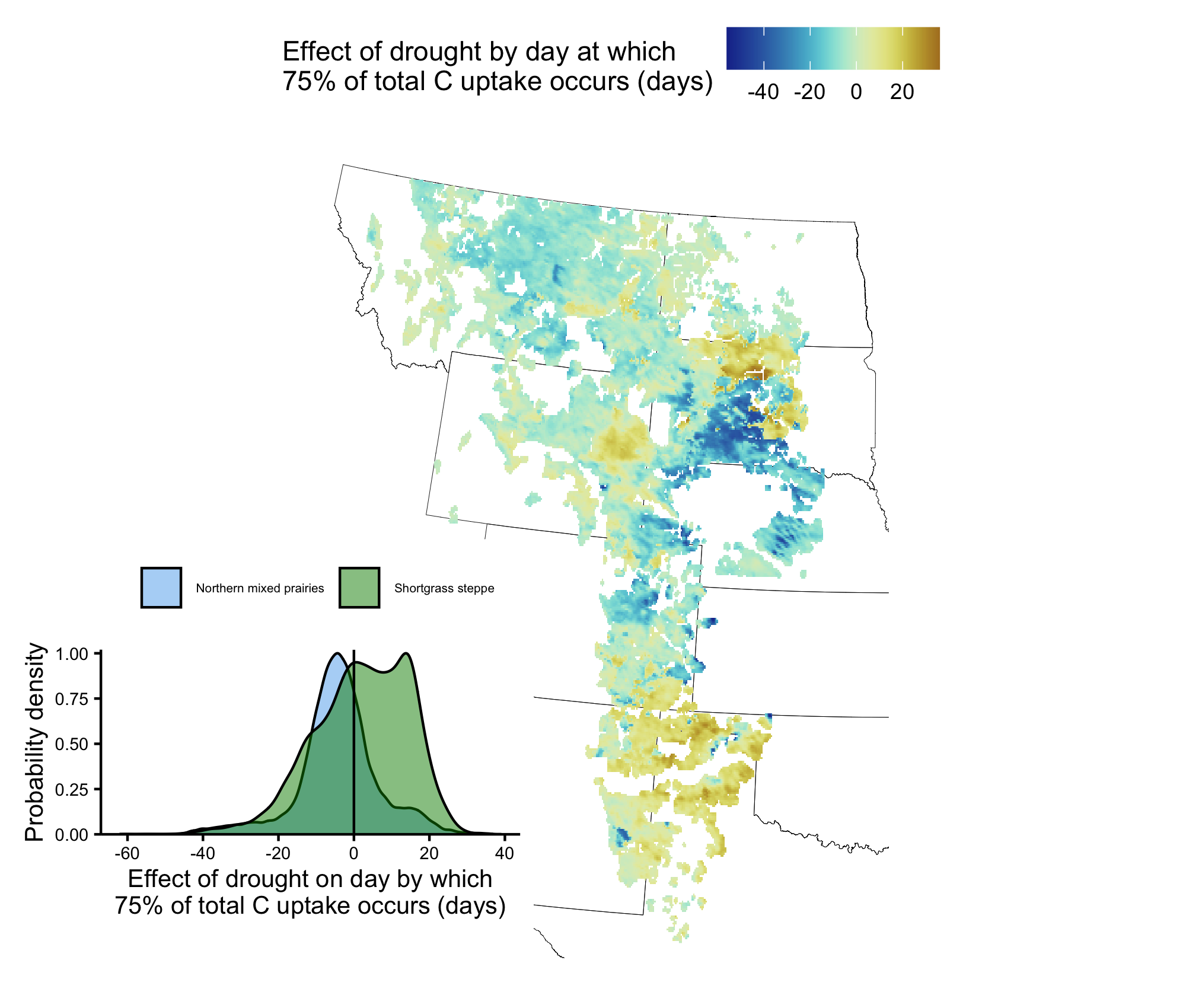
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**Figure S8. Time series of cumulative carbon uptake for the 1 km resolution subset of sites for each ecoregion.** Solid lines depict the median cumulative carbon uptake across sites in average (black line) and in drought years (red line), while the shading around each line depicts the interquartile range across sites (spatial variation).

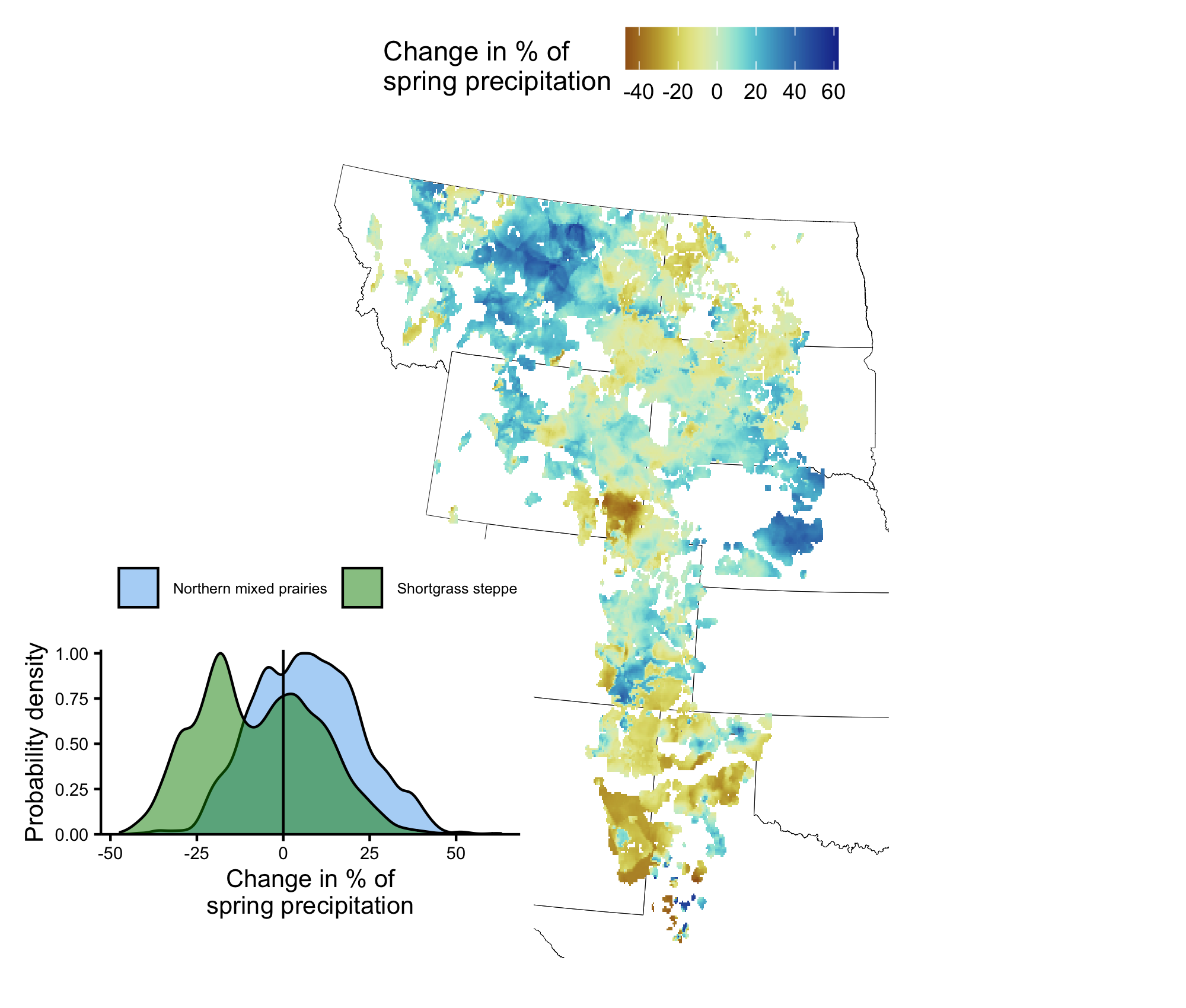
**Figure S9.** Spatial variation in drought impacts to total absolute carbon uptake. The map depicts spatial variation in the absolute changes in total (cumulative) carbon uptake during the driest year relative to non-drought years. The inset depicts probability density functions (scaled to 1) of these changes for each ecoregion.

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**Figure S10.** Drought impacts to the day by which 25% of total carbon uptake is reached. The map depicts spatial variation in these impacts during the driest year relative to non-drought years. The inset depicts probability density functions (scaled to 1) of these impacts for each ecoregion.

****

**Figure S11.** Drought impacts to the day by which 75% of total carbon uptake is reached. The map depicts spatial variation in these impacts during the driest year relative to non-drought years. The inset depicts probability density functions (scaled to 1) of these impacts for each ecoregion.

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**Figure S12.** Spatial variation in drought impacts to precipitation seasonality. The map depicts how the percent of meteorological spring precipitation (percent of total March-May precipitation relative to total March-August precipitation) changed during the driest years relative to non-drought years. A reduction in the percent of spring precipitation means an increase in the percent of meteorological summer (June-August) precipitation during the March-August period. The inset depicts probability density functions (scaled to 1) of these impacts for each ecoregion.