



# Article Quantifying the Impacts of Land-Use and Climate on Carbon Fluxes Using Satellite Data across Texas, U.S.

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Abstract: Climate change and variability, soil types and soil characteristics, animal and microbial communities, and photosynthetic plants are the major components of the ecosystem that affect carbon sequestration potential of any location. This study used NASA's Soil Moisture Active Passive (SMAP) Level 4 carbon products, gross primary productivity (GPP), and net ecosystem exchange (NEE) to quantify their spatial and temporal variabilities for selected terrestrial ecosystems across Texas during the 2015–2018 study period. These SMAP carbon products are available at 9 km spatial resolution on a daily basis. The ten selected SMAP grids are located in seven climate zones and dominated by five major land uses (developed, crop, forest, pasture, and shrub). Results showed  $CO_2$  emissions and uptake were affected by land-use and climatic conditions across Texas. It was also observed that climatic conditions had more impact on  $CO_2$  emissions and uptake than land-use in this state. On average, South Central Plains and East Central Texas Plains ecoregions of East Texas and Western Gulf Coastal Plain ecoregion of Upper Coast climate zones showed higher GPP flux and potential carbon emissions and uptake than other climate zones across the state, whereas shrubland on the Trans Pecos climate zone showed lower GPP flux and carbon emissions/uptake. Comparison of GPP and NEE distribution maps between 2015 and 2018 confirmed substantial changes in carbon emissions and uptake across Texas. These results suggest that SMAP carbon products can be used to study the terrestrial carbon cycle at regional to global scales. Overall, this study helps to understand the impacts of climate, land-use, and ecosystem dynamics on the terrestrial carbon cycle.

Keywords: gross primary productivity; net ecosystem exchange; climate; carbon dioxide; SMAP

# 1. Introduction

Global warming and climate change continue to be a subject of global interest. Climate change has and will continue to impact terrestrial ecosystems [1]. Feedbacks from the terrestrial ecosystems will also affect future climate change. There are several climate change mitigation methods that are being developed and evaluated. One of these methods is soil carbon sequestration, which attenuates climate change by acting as a carbon sink for anthropogenic  $CO_2$  emissions [2]. It is important to understand the carbon emissions and uptake dynamics of terrestrial ecosystems to study carbon sequestration potentials under changing climate [3].

Carbon sequestration potential of an ecosystem is a function of climate, land management practices, land-use patterns, soil types and soil characteristics, and topographic heterogeneity [4–10]. Some studies concurred that any ecosystem site could either be a carbon sink (negative flux) or a carbon source (positive flux) depending on the weather patterns [11,12]. However, an ecosystem can be a sink for carbon one year and source another, but it must be a sink for a longer period (>10 years)

to support carbon sequestration [13]. Ecosystem management also impacts carbon sequestration potentials. For example, deforestation and change in land-use cause loss of biomass and a significant amount of carbon dioxide to be released to the atmosphere [14].

Forests are known for their large atmospheric carbon sequestration potentials [15]. For example, 40% of the global terrestrial biomass is stored in tropical forests [16]. There are more long-term studies of  $CO_2$  dynamics in forests than in grasslands or any other ecosystem. However, carbon sequestration potential of grasslands and pastures is still debatable as some researchers demonstrate that these land uses are carbon neutral, while other researchers provide evidence that grasslands can be significant sources or sinks for atmospheric  $CO_2$  [17,18]. However,  $CO_2$  exchange between the land surface and atmosphere suggests that land surface could be managed to increase uptake and storage of  $CO_2$ , and thus become carbon sinks. Moreover, the loss of  $CO_2$  to the atmosphere by aerobic respiration is a non-linear function of temperature for a wide range of soil moisture content [19].

Several researchers have extensively studied the relationship between land-use change and spatiotemporal variation of carbon fluxes [20–23]. Some researchers found the concentration of atmospheric CO<sub>2</sub> increasing due to many anthropogenic activities, including land-use changes and burning of fossil fuels [24–28]. It is important to understand the effects of land-use change on carbon sequestration [5]. Deng et al. (2016) [29] conducted a literature review on the land-use change impact on the carbon cycle. The review covered research conducted in 29 countries at 160 different sites. They concluded land-use change has a significant impact on carbon stocks. However, they also deduced land-use change did not consistently result in either increasing or decreasing carbon stocks. For example, converting farmland to grassland or forestland to grassland increased the carbon stocks, whereas a conversion from grassland to farmland or forest to farmland decreased the carbon stocks.

Quantifying the atmospheric  $CO_2$  flux is necessary to determine the carbon sequestration potential of an ecosystem. Several  $CO_2$  monitoring approaches have been used to quantify carbon sequestration in an ecosystem such as biomass and soil carbon inventory studies using different sensing methods, for example, in-situ  $CO_2$  flux monitoring using eddy covariance flux tower, remote measurements through geostationary satellites, and ecosystem models [30]. However, in-situ  $CO_2$  measurements are limited and only available at a point scale, which cannot be used to study spatiotemporal distributions of  $CO_2$  at a larger scale [31–33]. Knowledge of quantifying the dynamic state of the terrestrial carbon cycle is important to understand the ecosystem response under a changing climate. However, it is difficult to measure and remains poorly quantified at a global scale [34].

An understanding of the relationship between regional carbon fluxes in the forms of gross primary productivity (GPP) and net ecosystem exchange (NEE) with environmental changes is necessary to understand the response of ecosystems to global climate changes [35–38]. GPP, a critical parameter for carbon cycle and climate change, is the total amount of carbon fixed by plants through photosynthesis in an ecosystem [39–42]. Accurate measurement or estimate of GPP is essential for the carbon cycle and climate change studies [43,44]. Net Ecosystem Exchange between the ecosystem and atmosphere represents the balance between GPP and ecosystem respiration and plays a critical role in climate change science [45,46]. NEE of the ecosystem is a measure of the balance between carbon uptake by vegetation GPP and carbon losses through total ecosystem respiration rate (Re), and loss due to disturbance [47]. The Re is the sum of plant autotrophic respiration (Ra) and soil heterotrophic respiration (Rh).

Gross primary productivity and NEE of ecosystems can also be quantified using process-based biogeochemical models [48] and satellite remote sensing [49]. For example, Byrne et al. (2018) [50] used four Terrestrial Biosphere Models (TBMs): (i) Carnegie-Ames Stanford Approach (CASA), (ii) Simple Biosphere model version 3 (SiB3), (iii) Canadian Terrestrial Ecosystem Model (CTEM), and (iv) Joint UK Land Environment Simulator (JULES) to examine GPP, NEE, and Re. On the other hand, Mao et al. (2017) [51] used the Boreal Ecosystem Productivity Simulator (BEPS) model to identify NEE for the bamboo forest. Remote sensing products such as vegetation type, NDVI, and other vegetation indices were used to estimate GPP [52]. One of the main advantages of satellite remote sensing method

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is that it estimates atmospheric  $CO_2$  at the global scale; however, its coarse spatial resolution is a major disadvantage [53]. On the other hand, satellite data combined with in-situ measurements and modeled data can be the best approach to monitoring and evaluating carbon fluxes at various spatial and temporal scales [51,54]. For example, Yi et al. (2013) [55] used the carbon flux model integrated with remotely sensed Normalized Difference Vegetation Index (NDVI) and in-situ meteorology data to quantify GPP and NEE over a pan-boreal/Arctic domain and found that drought and temperature had larger impacts on GPP and NEE.

Currently, there are various satellites in operation to estimate carbon fluxes globally [32]. For example, Soil Moisture Active Passive (SMAP) and Moderate Resolution Imaging Spectroradiometer (MODIS) are in operation to estimate NEE (SMAP)/NPP (MODIS) and GPP, respectively, at different spatial and temporal resolutions. Many studies have used MODIS GPP to study the carbon cycle associated with terrestrial ecosystems [56–58]. On the other hand, since SMAP was launched in 2015, only a few studies have used SMAP NEE and GPP to study the carbon cycle and terrestrial ecosystem [59,60].

The MODIS algorithm uses light use efficiency (LUE) model to estimate GPP, which may underestimate ecosystem GPP under varying climatic conditions and vegetation type and overestimate GPP for water-limiting ecosystems due to lack of explicit representation on soil moisture constraint [52]. In addition, MODIS estimates the GPP but leaves an incomplete picture of NEE due to lack of information on ecosystem respiration [47]. On the other hand, SMAP Level 4 carbon products algorithm incorporates soil moisture information, land cover classification and eight-day canopy fraction of photosynthetically active radiation (FPAR) observation from MODIS to provide detailed and improved estimations of terrestrial carbon fluxes [59,60].

This study used SMAP Level 4 carbon products to understand the spatial and temporal variability of carbon fluxes across Texas. Texas is unique among states because of its large size, geographical location, climate variations, and heterogeneous landscapes, which makes it unique to study ecosystem dynamics. The main goal of this research was to quantify the carbon sequestration potential across Texas and study the combined effects of climate and land-use changes on it. Thus, the specific objectives of this work were to: (1) Evaluate SMAP NEE and GPP products; (2) quantify spatial patterns and temporal distributions of  $CO_2$  flux across Texas; and (3) evaluate the response of  $CO_2$  fluxes to the combined effects of climate and land-use changes in the state of Texas using SMAP Level 4 carbon products.

#### 2. Materials and Methods

#### 2.1. Study Area

The study area Texas (area = 695,622 km<sup>2</sup>) has ten climate zones and 12 ecological regions [61,62]. The ten climate zones are: High Plains (HP), Low Rolling Plains (LRP), East Texas (ET), Edwards Plateau (EP), South Central (SC), Trans Pecos (TP), Upper Coast (UC), North Central (NC), Southern (S), and Lower Valley (LV). The twelve ecoregions are: Arizona/New Mexico Mountains (ANM), Chihuahuan Deserts (CD), High Plains (HP), Southwestern Tablelands (SWT), Central Great Plains (CGP), Cross Timbers (CT), Texas Blackland Prairies (TBP), Edwards Plateau (EP), East Central Texas Plains (ECTP), South Central Plains (SCP), Southern Texas Plains (STP), and Western Gulf Coastal Plain (WGCP) (Figure 1). All of the climate zones have multiple ecoregions, which show significant diversity in landscapes, topography, and land-use in the state. ANM ecoregion is very small in area and can be included in CD ecoregion. CD ecoregion has desert valleys, plateaus, and wooded mountains, and receives the lowest precipitation in the state. HP ecoregion, a relatively high-level plateau, is mostly covered with cropland. SWT and CGP ecoregions are located in north-central Texas. CT is covered with high-density trees and regular plains and prairies, whereas TBP is covered with tall grass and prairies. EP ecoregion, known as the Texas Hill Country, has many springs, stony hills, and steep canyons. SCP,

located in south-west Texas, is covered with thorny shrubs and trees and scattered patches of palms and subtropical woodlands, whereas WGCP, located along the coast of Gulf of Mexico, is covered with cropland, tall prairies, and marshland. SCP and ECTP ecoregions are dominated by forestland and pastureland, respectively. SCP ecoregion is covered with pines and oaks and characterizes the forest of the East Texas Pinewoods, whereas ECTP ecoregion is covered with strips of prairie grassland and can be described as oak savannah mixed with grassland [63].



**Figure 1.** (a) Climate zones and their corresponding land-use, and (b) ecological regions and climate zones in the study area. White crosses are the locations of ten select Soil Moisture Active Passive (SMAP) grids. The inset figure (9 km × 9 km, not in scale) is a selected SMAP grid, covering Prairie View A&M University (PVAMU) research farm, to evaluate SMAP Gross Primary Productivity (GPP) and Net Ecosystem Exchange (NEE).

Texas is dominated by deserts, pine forests, shrubland, and cropland. It shares the Rio Grande River with Mexico, and its size and physical geography influence its diverse climate. Three geographical features, which significantly influence the climate of Texas, are the Rocky Mountains, Central and Eastern parts of the continent of North America, and the Gulf of Mexico. The Rocky Mountains influence Texas climate by acting as a barrier to air traveling from east to west or west to east. While the Central and Eastern parts of the continent of North America act as a pathway for airflow into Texas, the Gulf of Mexico, a source of moisture, helps to moderate Texas temperature [64].

Ten research sites (ten SMAP grid cells) from seven climate zones, which include five major land uses, were selected in this study. We selected only one SMAP grid cell from each land-use because the size of one grid cell is 9 km by 9 km, which is large enough to cover homogenous agricultural field or landscape of selected land-use type.

The selected climate zones are HP, ET, EP, SC, TP, UC, and NC (Figure 1). The Upper Coast climate zone receives the highest amount of precipitation, whereas the Trans Pecos receives the lowest amount of precipitation in Texas (Figure 2). In general, the climate zones of the eastern and southern parts of the state receive higher rainfall compared to the climate zones located in the north and west. Texas' climate varies widely across the state, from humid and hot in the east and south to arid and cool in the west and north (Figure 2). The temperature gradually increases from south-east to north-west across the state. Forests are the predominant land-use type in the eastern parts, whereas shrublands are the predominant land-use type in the state. However, most southern and northern regions of the state are dominated by cropland.

![](_page_4_Figure_1.jpeg)

**Figure 2.** Cumulative distribution of precipitation (**a**), and average annual distribution of temperature across Texas (**b**) using precipitation and temperature data from 2001–2018. The cumulative precipitation plot for each climate zone was developed using National Climatic Data Center (NCDC) daily precipitation data, whereas the annual average temperature (calculated using NCDC daily temperature data) was used to develop the spatial average temperature map across Texas. The x-axis of the cumulative distribution of the precipitation plot includes a fraction of time, which means 0.5 represents 50% of the time (9 years for this plot), and 1.0 represents 100% of the time (18 years for this plot).

This study includes five major land uses: Cropland, forestland, pastureland, shrubland, and open-developed land. Two research sites, dominated by cropland, are located at UC and HP climate zones and WGCP and HP ecoregions, whereas two research sites, dominated by forestland, are located at ET and TP climate zones and SCP and CD ecoregions. Similarly, two research sites, dominated by pastureland, are located at ET and NC climate zones and ECTP, and TBP ecoregions; two research sites, dominated by shrubland, are located at TP and EP climate zones and EP and CD ecoregions; and two research sites, dominated by developed land, are located at ET and SC climate zones and WGCP and TBP ecoregions. These climate zones and their corresponding land uses and ecoregions are shown in Figure 1 and Table 1. The geophysical characteristics of each location are also presented in Table 1.

Location	Latitude (°)	Longitude (°)	Climate Zone	Ecoregion	Land-Use	Soil Texture
UC Cropland	29.03	-96.19	UC	WGCP	Cropland	Sandy Loam
HP Cropland	33.15	-102.27	HP	HP	Cropland	Sand
ET Forestland	31.18	-94.75	ET	SCP	Forestland	Loam
TP Forestland	30.69	-104.12	TP	CD	Forestland	Silt Loam
ET Pastureland	31.04	-95.89	ET	ECTP	Pasture Hay	Loam
NC Pastureland	31.48	-96.88	NC	TBP	Pasture Hay	Clay
TP Shrubland	30.71	-102.79	TP	CD	Shrubland	Loam
EP Shrubland	30.86	-100.21	EP	EP	Shrubland	Clay
ET Developed land	30.08	-95.98	ET	WGCP	Developed land	Sandy Loam
SC Developed land	29.93	-97.69	SC	TBP	Developed land	Clay

**Table 1.** Research site locations (center of the SMAP grid cell) and their corresponding climate zone, land-use, and soil texture. Note: Full names of climate zone and ecoregion are presented in Figure 1.

#### 2.2. Data

This study used SMAP Level 4 carbon products (L4C) available at 9 km spatial and daily temporal resolutions [47,65]. Soil Moisture Active and Passive (SMAP), an environmental research satellite, was launched on 31 January 2015, by the National Aerospace Space Administration (NASA) to monitor global carbon fluxes, soil moisture and freeze/thaw state at different spatial and temporal resolutions using radar and radiometric instruments. However, with the failure of the SMAP active radar, only passive data were available from 31 March 2015, onwards.

This study relied on model-derived data products of surface and root zone soil moisture and carbon net ecosystem exchange compiled using SMAP L4C products, which provided daily estimates of NEE to determine the spatial and temporal patterns of CO<sub>2</sub> fluxes across Texas. This study also analyzed modeled SMAP GPP component to understanding the spatial and temporal distributions of GPP for five major land-use categories in seven different climate zones across Texas.

The SMAP NEE is not a direct measurement or observation from the satellite, rather, it is a modeled estimate which includes daily root-zone soil moisture inputs to constrain GPP, surface soil moisture to constrain heterotrophic respiration (Rh), and other input parameters to estimate daily NEE [60]. Uncertainty is reported on an annual basis as NEE root mean square error (RMSE) considering all sources of errors such as input data (e.g., temperature, soil moisture), heterogeneity (e.g., land-use heterogeneity), and model parameterization. The total annual and daily uncertainty are estimated as  $30 \text{ g C m}^{-2} \text{ year}^{-1}$  and  $1.6 \text{ g C m}^{-2} \text{ d}^{-1}$ , respectively [47]. John et al. [60] validated SMAP NEE using in-situ EC flux tower observations from 26 validation sites located all over the world. They found NEE performance within the targeted accuracy threshold (RMSE  $\leq 1.6 \text{ g C m}^{-2} \text{ d}^{-1}$ ) for NEE over 66% of the global domain.

SMAP L4C products were obtained from Earthdata web-based database developed by NASA called the Earth Observing System Data Information System (EOSDIS) [66]. The 2011 land-use data, used in this study, were obtained from the National Land Cover Database (NLCD) [67]. The NLCD provides nationwide land-use data at a 30-m spatial resolution.

#### 2.3. Methods and Analysis

This study used SMAP L4C daily products from 1 April 2015 to 31 December 2018. The daily GPP and NEE estimates were converted into monthly. Monthly (for selected six months) spatial maps of GPP and NEE were developed for each land-use and associated climate zone during the study period. The monthly values of the GPP and NEE data were used to develop time series plots at ten sites to understand the temporal variations of  $CO_2$  flux at each location associated with particular land-use. These graphs were used to quantify the temporal and seasonal variations of  $CO_2$  flux as extracted from SMAP Level 4 carbon products. These time series plots were also used to compare the GPP and NEE for the different land uses during the study period.

The SMAP NEE and GPP data were evaluated at Prairie View A&M University (PVAMU) site at satellite footprint (Resolution = 9 km), which was an open-developed area. An eddy covariance (EC) flux tower was installed (April 2016) at PVAMU to monitor carbon fluxes and climatic and hydrologic variables. SMAP NEE and GPP products were evaluated using in-situ NEE and GPP data. The half-hourly CO<sub>2</sub> flux data were used to estimate daily NEE and GPP. Assuming loss of disturbance negligible, NEE data were partitioned into GPP and Re using GPP = Re – NEE, where daytime NEE is the difference between GPP and Re and night-time NEE is equal to ER. Therefore, GPP is negligible during the night-time.

It should be noted that no other EC flux tower's measurements were available in the state during the study period. Therefore, no other locations were used to validate SMAP GPP and NEE measurements. A sequence of time series plots was developed to identify the sensitive months when GPP and NEE values were changing or abruptly changed during the study period. Based on the changes in seasonal distributions of GPP and NEE, six different months (Apr, May, Jun, Aug, Sep, and Dec) of 2015 and 2018 were used to develop spatial distribution maps of GPP and NEE (Figure 3).

![](_page_6_Figure_1.jpeg)

**Figure 3.** Daily gross primary productivity (GPP) and NEE at Upper Coast (UC) and High Plains (HP) for cropland during 2015 and 2016 to select the critical month of each year to develop spatial distribution maps. A sequence of time series plots was developed to identify the sensitive months when GPP and NEE values were changing or abruptly changed during the study period. Based on the changes in seasonal distributions of GPP and NEE, six different months (Apr, May, Jun, Aug, Sep, and Dec) of 2015 and 2018 were used to develop spatial distribution maps of GPP and NEE.

In addition, changes in spatial coverage between 2015 and 2018 for specified GPP/NEE range were calculated. First, the spatial area for specified NEE and GPP ranges were calculated for the selected months of 2015 and 2018 (Table 2). Then, the change in spatial coverage of specified NEE and GPP ranges between the selected months of 2015 and 2018 were calculated by subtracting the spatial area of specified GPP and NEE ranges of 2015 from 2018 for each month. ArcGIS (Spatial Analyst-Zonal Statistics tool) was used to summarize average GPP and NEE for all of the selected land-use categories in each climate zone [68].

The daily GPP and NEE values (g C m<sup>-2</sup> d<sup>-1</sup>) were used to estimate annual GPP and NEE values (g C m<sup>-2</sup> year<sup>-1</sup>) in each climate zone (Table 3). First, annual GPP and NEE were estimated at each pixel in every climate zone. Then, average GPP and NEE were computed in each climate zone. Additionally, GPP and NEE values were used to calculate the standard deviation (SD) of annual carbon fluxes each year in each climate zone. Since SMAP L4C data were available only for nine months in 2015, this year was excluded from the analysis.

The monthly GPP and NEE (2015–2018) data from two climate zones with the same land-use were used to calculate the coefficient of determination ( $\mathbb{R}^2$ ) and *p*-values each year. Box and whisker plots were developed using monthly GPP and NEE values at select locations of each climate zone dominated by one of five major land uses across Texas.

NEE. (g C m <sup>-2</sup> mo <sup>-1</sup> )	Apr	May	Jun	Aug	Sep	Dec	GPP (g C m <sup>-2</sup> mo <sup>-1</sup> )	Apr	May	Jun	Aug	Sep	Dec
-175 to -150		0.01	-0.05	-0.06			0 to 50	25.70	17.67	19.02	-8.15	-4.82	16.48
-149 to -125		0.05	-0.04	-0.15			51 to 100	-11.43	6.21	23.75	-21.55	-15.39	-15.75
-124 to -100		0.15	-0.02	-0.28			101 to 150	-6.22	-8.28	2.24	-10.89	21.05	-0.72
-99 to -75		0.73	-7.94	-0.57	-0.08		151 to 200	-14.80	-14.04	-13.65	4.06	2.48	
-74 to -50	0.04	0.92	-42.17	-2.49	-2.55		201 to 250	6.40	-8.39	-19.06	8.46	-1.92	
-49 to -25	8.42	3.38	-13.18	-13.97	-17.15		251 to 300	0.34	5.75	-11.82	6.28	-1.18	
-24 to 0	-15.92	-30.90	32.30	-7.74	-18.44	-4.41	301 to 350		0.77	-0.66	7.58	-0.20	
1 to 25	10.77	24.71	30.99	25.25	36.18	5.14	351 to 400		0.27	0.18	5.71	-0.01	
26 to 50	-3.27	0.85	0.11		2.05	0.20	>400		0.04		8.49		
51 to 75	-0.04	0.06				-1.10							
76 to 100						0.17							

**Table 2.** Change in spatial coverage of specified (particular) NEE and GPP ranges between selected months of 2018 and 2015 across Texas. All of the values for respective months are in percentage.

Climate Zone	GP	PP (g C m <sup>-2</sup> year	r <sup>-1</sup> )	NEE (g C m <sup><math>-2</math></sup> year <sup><math>-1</math></sup> )			
	2016	2017	2018	2016	2017	2018	
HP	811 (207)	811 (216)	625 (199)	-90.2 (42)	-93.2 (47)	23.2 (45)	
LRP	897 (139)	819 (115)	616 (117)	-102.4 (41)	-86.4 (32)	57.1 (31)	
NC	1402 (198)	1241 (194)	1032 (191)	-160.7 (40)	-98.9 (37)	41.3 (28)	
ET	1907 (161)	1818 (187)	1657 (217)	-102.4 (47)	-66.4 (47)	42.1 (62)	
TP	525 (133)	478 (121)	408 (103)	-64.9 (45)	-47.7 (42)	0.1 (34)	
EP	1093 (229)	944 (204)	820 (203)	-149.4 (51)	-87.1 (41)	3.1 (42)	
SC	1623 (210)	1490 (248)	1366 (231)	-206.7 (56)	-150.0 (51)	-57.1 (44)	
UC	2070 (348)	2027 (355)	1941 (352)	-89.6 (62)	-90.6 (64)	-30.4 (66)	
S	1219 (211)	1065 (188)	1056 (198)	-149.7 (79)	-78.9 (67)	-44.9 (59)	
LV	1540 (369)	1444 (375)	1411 (325)	-65.7 (55)	-9.6 (56)	48.8 (84)	

**Table 3.** Annual NEE and GPP estimates in each climate zone across Texas. The standard deviation (SD) values are presented inside parentheses.

# 3. Results

#### 3.1. Evaluation of Satellite CO<sub>2</sub> Using In-Situ Measurements

Open-developed land of the PVAMU research farm, located in East Texas climate zone, was used to evaluate SMAP NEE product. Net ecosystem exchange data were collected from the EC flux tower at 30-min intervals and converted into daily and monthly values. The footprint area of SMAP satellite is 9 km  $\times$  9 km, while the flux tower has a 400 m  $\times$  400 m footprint area. This study compared daily and monthly in-situ and SMAP GPP and NEE (Figure 4). Despite considerable scale difference between these two measurements, there were reasonable agreements between in-situ measurements and SMAP GPP and NEE estimates. In addition, the agreement was better during certain months than others. For example, Figure 4 shows reasonable agreement between in-situ measurements and SMAP NEE estimates during the June–August, and November–December periods. However, GPP showed better agreement during the winter. At most of the ecosystems, carbon productivity tended to increase during summer and reduce during winter while carbon exchange tended to be negative (carbon sinks) during summer and positive (carbon sources) during winter (Figure 4). For a quantitative assessment, the performance of SMAP NEE and GPP were evaluated using correlation coefficient (R), and root mean square error (RMSE). The correlation coefficient of 0.42 and 0.43 (daily) and 0.54 and 0.67 (monthly), respectively, for NEE and GPP, can be considered a reasonable agreement between in-situ measurements and SMAP estimates considering the scale difference between the two datasets. In addition, RMSE of 2.42 g C m<sup>-2</sup> d<sup>-1</sup> and 32.1 g C m<sup>-2</sup> mo<sup>-1</sup>, respectively, for daily and monthly NEE values can generally be considered good, but are higher than the estimated uncertainty threshold which is mainly due to the land-use heterogeneity at this location. Additionally, RMSE of 2.96 g C m<sup>-2</sup> d<sup>-1</sup> and 62.5 g C m<sup>-2</sup> mo<sup>-1</sup>, respectively, for daily and monthly GPP values can also be considered reasonable at these scales.

![](_page_9_Figure_1.jpeg)

**Figure 4.** Daily and monthly SMAP and in-situ GPP and NEE at PVAMU Research Farm (2016–2018). The unit of RMSE is the same as of GPP and NEE.

#### 3.2. Carbon Fluxes at Different Climate Zones

Annual and monthly GPP and NEE values were compared in each climate zone for the selected months from 2015 to 2018 (Figures 5 and 6 and Table 3). While some climate zones showed higher GPP and NEE values in one year than another year, others showed lower. For example, each climate zone showed high GPP values from spring to fall and low in winter each year; however, in comparison, UC and ET climate zones showed the highest GPP values and TP and EP climate zones showed lowest GPP values during the same period. Each of the selected climate zones, which had highest GPP (168–479 g C m<sup>-2</sup> mo<sup>-1</sup>) in August 2018 except EP, S, and LRP climate zones, which had highest GPP in June 2015 (154–190 g C m<sup>-2</sup> mo<sup>-1</sup>), and TP climate zone which had highest GPP in September 2016 (82 g C m<sup>-2</sup> mo<sup>-1</sup>). Each of the selected climate zones showed the lowest GPP in December, but not necessarily in the same year. For example, all of the climate zones had lowest GPP in December 2017 (22–51 g C m<sup>-2</sup> mo<sup>-1</sup>) because hurricane Harvey (late summer in 2017) brought heavy precipitation, which may cause change in vegetation growth in some of the climate zones (Figure 5).

In addition, each climate zone showed the highest carbon emission (+ve NEE) and carbon uptake (-ve NEE), respectively, in December (13.3–52.1 g C m<sup>-2</sup> mo<sup>-1</sup>) and in June (-74.3 to -47.3 g C m<sup>-2</sup> mo<sup>-1</sup>), except HP and TP climate zones, which had the highest carbon emissions and carbon uptakes, respectively, in May (6.8–12.2 g C m<sup>-2</sup> mo<sup>-1</sup>) and in June (-49 to -22.6 g C m<sup>-2</sup> mo<sup>-1</sup>).

UC and ET climate zones had the highest NEE in December and April 2016 (43.8 and 52.1 g C m<sup>-2</sup> mo<sup>-1</sup>), whereas the lowest NEE (-63.2 and -58.5 g C m<sup>-2</sup> mo<sup>-1</sup>) in June 2016 and 2015. In 2015, NC and LRP climate zones had the highest and lowest NEE in December and June (NC/LRP; 21.3/13.3 and -66.2/-47.3 g C m<sup>-2</sup> mo<sup>-1</sup>), respectively. Five climate zones (SC, ET, S, LV, and EP) showed highest NEE (12.4–43.8 g C m<sup>-2</sup> mo<sup>-1</sup>) in December 2016 and lowest NEE (-74.3 to -47.7 g C m<sup>-2</sup> mo<sup>-1</sup>). However, two climate zones (NC and LRP) showed the highest and lowest NEE (NC/LRP; 21.3/13.3 and -66.2/-47.3 g C m<sup>-2</sup> mo<sup>-1</sup>) in 2015.

![](_page_10_Figure_1.jpeg)

Figure 5. Distributions of monthly GPP in each climate zone (2015–2018).

![](_page_11_Figure_1.jpeg)

Figure 6. Distributions of monthly NEE in each climate zone (2015–2018).

Compared to August 2015, the largest spatial change in GPP was observed in August 2018 in UC, ET, SC, S, and some portions of EP and NC climate zones. However, the lowest change in GPP was observed in December in all climate zones except some portion of the UC climate zone (Figure 7). In addition, all climate zones except some portions of UC and ET climate zones showed a change in

carbon emission and uptake in June. HP, TP, and some portions of EP and LRP climate zones showed a change in carbon uptake in April and May (Figure 8). Compared to 2016 and 2017, HP and NC climate zones had lower GPP in 2018 (Figure 9). Besides, there was a decreasing trend in carbon uptake from 2016 to 2017.

![](_page_12_Figure_3.jpeg)

**Figure 7.** Spatial distribution of GPP across Texas for selected months of 2015 and 2018. White crosses are the location of selected SMAP grids.

![](_page_13_Figure_2.jpeg)

**Figure 8.** Spatial distribution of NEE across Texas for selected months of 2015 and 2018. White crosses are the location of selected SMAP grids.

In comparison, carbon uptake changed into carbon emission in most of the climate zones in 2018 (Figure 9). One of the main reason for this change was the impact of wetness (rain), which increased from 2015 to 2017 and decreased in 2018. Each climate zone had different annual GPP, but UC and TP climate zones had the highest (1941–2070 g C m<sup>-2</sup> year<sup>-1</sup>) and the lowest (408–525 g C m<sup>-2</sup> year<sup>-1</sup>) annual GPP each year, respectively. In addition, TP climate zone had the lowest spatial variability (SD = 103–133 g C m<sup>-2</sup> year<sup>-1</sup>) each year, but UC climate zone had highest spatial variability (SD = 352 g C m<sup>-2</sup> year<sup>-1</sup>) in 2018, whereas LV climate zone had highest spatial variability (SD = 369–375 g C m<sup>-2</sup> year<sup>-1</sup>) in 2016 and 2017. Each climate zone showed a decreasing

trend of annual GPP from 2016 to 2018. HP and LRP climate zones showed similar annual GPP each year, but HP climate zone had larger spatial variability than LRP climate zone. Similarly, SC and LV climate zones showed similar annual GPP each year, but LV climate zone had larger spatial variability than LRP climate zone (Table 3).

![](_page_14_Figure_2.jpeg)

**Figure 9.** Annual distribution of GPP (**a**–**c**) and NEE (**d**–**f**) across Texas. White crosses are the location of selected SMAP grids.

All climate zones showed carbon uptake in 2016 and 2017, and carbon release in 2018 except UC, SC and S climate zones, which continuously showed carbon uptake from 2016 to 2018. Each climate zone showed a decreasing trend of annual carbon uptake from 2016 to 2018 except HP and UC climate zones, which had slightly higher carbon uptake in 2017 than 2016. LV climate zone showed the highest annual carbon release (48.8 g C m<sup>-2</sup> year<sup>-1</sup>) in 2018 and lowest annual carbon uptake (-9.6 g C m<sup>-2</sup> year<sup>-1</sup>) in 2017. On the other hand, highest annual carbon uptake (-206.7 g C m<sup>-2</sup> year<sup>-1</sup>) was observed in SC climate zone in 2016, and lowest annual carbon release (0.1 g C m<sup>-2</sup> year<sup>-1</sup>) was observed in TP climate zone in 2018. In 2018, the largest (84 g C m<sup>-2</sup> year<sup>-1</sup>) and smallest (28 g C m<sup>-2</sup> year<sup>-1</sup>) spatial variability in annual NEE were observed in LV and NC climate zones, respectively.

#### 3.3. Spatial Distributions of Carbon Fluxes for the Selected Major Land Uses

Figures 7 and 8 compare the spatial distribution of monthly GPP and NEE between 2015 and 2018 in all climate zones. In addition, Table 2 compares the change in spatial coverage of specified NEE and GPP ranges between selected months of 2018 and 2015 across Texas. Based on the estimated GPP range during the study period, this study assumed monthly GPP values >301, 100 to 300, and <100 g C m<sup>-2</sup> mo<sup>-1</sup>, respectively, as a high, an average, and a low GPP. Similarly, NEE values >75, 25 to 75, and <0–25 g C m<sup>-2</sup> mo<sup>-1</sup>, respectively, assumed to be high, average, and low carbon emissions, whereas NEE values <-75, -25 to -5, and >-25 and <0, g C m<sup>-2</sup> mo<sup>-1</sup>, respectively, assumed to be high, average, and low carbon uptakes during the study period. These classifications will help to compare GPP and NEE values at a different location across Texas. To interpret the changes between 2015 and 2018, the GPP and NEE values were grouped into nine and eleven classes, respectively (Table 2). All of the positive values indicate 2018 had higher spatial coverage for particular NEE and GPP ranges than 2015, whereas all of the negative values indicate 2015 had higher spatial coverage for particular NEE and GPP ranges than 2018.

#### 3.3.1. Spatial Distributions of GPP

All climate zones showed low GPP in December 2015 and 2018. UC and ET climate zones showed higher GPP during May–September in 2015 and May–August in 2018 than other months. In comparison, the observed monthly GPP from May to September in 2015 was lower than in 2018. For example, UC and ET climate zones showed GPP > 401 g C m<sup>-2</sup> in August 2018 and <400 g C m<sup>-2</sup> in August 2015. Forest and pasturelands of ET climate zone showed GPP increased from April to June in 2015, and April to May in 2018, but decreased from May to June in 2018. On the other hand, cropland of UC climate zone had higher GPP than the HP climate zone during the study period, which shows these two locations had a different climate (Figure 7).

Forestland of ET and TP climate zones had different GPP distributions during the study period. The observed GPP in ET climate zone was low to high (51–100 g C m<sup>-2</sup> mo<sup>-1</sup> (December) to >400 g C m<sup>-2</sup> mo<sup>-1</sup> (August)), whereas it was low (<50 g C m<sup>-2</sup> mo<sup>-1</sup> (December)) to average (101–150 g C m<sup>-2</sup> mo<sup>-1</sup> (August)) in the TP climate zone during the study period. On the other hand, GPP decreased from August to September in 2015 and 2018 at both climate zones. The pasture-dominated region of ET and NC climate zones showed an increasing trend from April to June and decreasing trend from August to December. However, ET climate zone had higher GPP than NC climate zone (Figure 7).

The eastern portions of TP and EP zones were dominated by shrubland. Shrubland in TP climate zone showed low GPP throughout the study period except in August 2018, whereas EP climate zone showed an average GPP, but an increasing trend from April to June in 2015 and an increasing trend from April to May, but a decreasing trend from May to June in 2018. However, EP zone showed a decreasing trend of GPP from August to December. In August 2018, shrubland-dominated areas of TP and EP climate zones showed the average and high GPP, respectively. The developed land of ET climate zone showed higher GPP than the SC climate zone each month during the study period, except in December when both zones showed low GPP (Figure 7).

During April to June, and December, the area with low GPP ( $<50 \text{ g C m}^{-2} \text{ mo}^{-1}$ ) increased by 16 to 26% in 2018 from 2015, whereas during August and September, it decreased by 5 to 8% (Table 2). While there were no consistent changes in spatial coverage observed for the particular GPP ranges in any month, some of the months had higher changes in spatial coverage for low to average (0 to 300 g C m<sup>-2</sup> mo<sup>-1</sup>) GPP range, whereas other months had higher changes in spatial coverage for high GPP range (>301 g C m<sup>-2</sup> mo<sup>-1</sup>). For example, May and August 2018 had, respectively, 0.04% and 8.49% more area than 2015, having GPP greater than 400 g C m<sup>-2</sup> mo<sup>-1</sup>. The changes in spatial coverage analysis showed 16.47% more area in December 2015 had GPP from 51 to 150 g C m<sup>-2</sup> mo<sup>-1</sup> than in December 2018. In addition, 32.45% more area in April 2015 had GPP from 51 to 200 g C m<sup>-2</sup> mo<sup>-1</sup> than in 2015 whereas, in September, 0.21% more area had GPP from 301 to 400 g C m<sup>-2</sup> mo<sup>-1</sup> in 2018 than in 2015. However, in June, 0.66% more, and 0.18% less area had GPP from 301 to 400 g C m<sup>-2</sup> mo<sup>-1</sup> in 2015 than in 2018 than in 2015 (Table 2).

The analysis showed warmer and wetter climate zones, and months had higher GPP than the cooler and dryer zones and months during the study period. Moreover, some croplands and forestland showed higher GPP than shrub and pasturelands.

#### 3.3.2. Spatial Distributions of NEE

NEE is used to quantify carbon uptake (-ve NEE) and carbon release or emission (+ve NEE) of a given ecosystem. All climate zones showed carbon emission in December except some portion of the climate zones located along the western boundary of Texas. UC and ET climate zones had high carbon emission in December, whereas UC and LV climate zones had high carbon uptake in June. However, the HP climate zone had high carbon uptake in August (Figure 8).

NEE (either carbon emission or carbon uptake) values from two different land uses at one climate zone, or the same land-use at two different climate zones were not consistent during the study period.

For example, cropland of UC and HP climate zones had, respectively, carbon emission and carbon uptake in April 2015, which were reversed in April 2018 (Figure 8). The carbon emission rate decreased from April to June and increased from August to December each year in these two climate zones.

Forestland of ET and TP zones had significantly different NEE each month except August and September. For example, ET and TP climate zones had carbon emissions and carbon uptakes, respectively, in April 2015, which were reversed in April 2018. In December, TP climate zone had low carbon emission, whereas ET climate zone had high carbon emission. Pastureland of ET and NC climate zones showed similar NEE distributions each month, except September and December. Pastureland of ET climate zone had high carbon emission, whereas the NC climate zone had low carbon emission in December each year. However, ET and NC climate zones had low carbon emission and low carbon uptake, respectively, in September 2018, whereas both climate zones had similar NEE distributions in September 2015.

Shrubland of EP and TP climate zones had low carbon uptakes in April and May 2015 and low carbon emissions in April and May 2018, respectively. Both climate zones had average carbon uptakes in June 2015 and low carbon emissions in June 2018. However, both climate zones had similar NEE distributions from August to December. Developed land of both climate zones showed similar NEE distributions from April to June 2015 and April to May 2018 and different NEE distributions during the rest of the months. For example, developed land of the ET climate zone showed an average carbon emission, whereas the SC climate zone showed low carbon emission in December 2015 and 2018. Similarly, developed land of the ET climate zone had an average carbon uptake, and the SC climate zone had low carbon uptake from August to September in 2015 and 2018 (Figure 8).

In May, the area with high carbon uptake ( $<-75 \text{ g C m}^{-2} \text{ mo}^{-1}$ ) increased by 0.94% in 2018 from 2015; then in June and August, it decreased by 9.1% (Table 2). While there were no consistent changes in spatial coverage observed for particular NEE ranges in any month, some of the months had higher changes in spatial coverage for an average ( $-74 \text{ to } -25 \text{ g C m}^{-2} \text{ mo}^{-1}$ ) NEE range, whereas other months had higher spatial changes for low NEE range ( $-24 \text{ to } 0 \text{ g C m}^{-2} \text{ mo}^{-1}$ ). Areas with carbon emission range  $-74 \text{ to } -25 \text{ g C m}^{-2} \text{ mo}^{-1}$  in June 2018 were 55.37% lower than in June 2015. However, each month in 2018, carbon uptake range 1 to 25 g C m<sup>-2</sup> mo<sup>-1</sup>, had a higher area than in 2015 (Table 2). The changes in spatial coverage analysis showed 4.41% more area had low carbon uptake ( $-24 \text{ to } 0 \text{ g C m}^{-2} \text{ mo}^{-1}$ ) in December 2015 than in December 2018 and 15.92% more area had low carbon uptake in April 2015 than in April 2018. In May, 30.9% more area had low carbon uptake in 2015 (Table 2).

The analysis showed, in comparison, warmer and dryer climate zones and months had more carbon emission than the warmer and wetter zones. However, the dryer and cooler climate zones and months had more carbon uptakes across the state.

#### 3.4. Temporal Distributions of Carbon Fluxes for the Selected Major Land Uses

The temporal distribution of monthly GPP and NEE of each land-use category in one climate zone was compared with the distribution of monthly GPP and NEE of the same type of land-use in another climate zone. Time series plots of monthly precipitation, temperature, GPP, and NEE were developed across all ten locations to understand the temporal variations of these parameters for ten ecosystems during the study period (Figure 10). Graphs of each land-use in two different climate zones showed monthly and seasonal variations of precipitation, temperature, GPP, and NEE (Figure 10). Monthly GPP and NEE values were plotted to observe variations in the rate of carbon production and CO<sub>2</sub> exchange during the study period for each land-use.

![](_page_17_Figure_2.jpeg)

**Figure 10.** Temporal distributions of monthly precipitation, GPP ( $\mathbf{a}-\mathbf{e}$ ) and NEE ( $\mathbf{f}-\mathbf{j}$ ) of five major land-use categories: Cropland (crop), forestland (forest), pastureland (pasture), shrubland (shrub) and developed land (developed) at each selected climate zone in Texas. Note: HP = High Plains; LRP = Low Rolling Plains; ET = East Texas; EP = Edwards Plateau; SC = South Central; TP = Trans Pecos; UC = Upper Coast; NC = North Central; S = Southern; LV = Lower Valley.

## 3.4.1. Temporal Distributions of GPP

Developed land of ET climate zone showed higher monthly GPP as compared to SC climate zone (Figure 10a). Both locations had higher GPP during the summer and lower GPP during the winter. ET climate zone had highest and lowest GPP (404 and 42 g C m<sup>-2</sup> mo<sup>-1</sup>) in July 2015 and December 2018, whereas SC climate zone had the highest and lowest GPP (224 and 33 g C m<sup>-2</sup> mo<sup>-1</sup>) in June 2015 and December 2018. Each summer, except 2018, compared to other seasons, these climate zones received higher precipitation during the study period. However, ET climate zone received more precipitation than the SC climate zone. R<sup>2</sup> and *p*-values (0.78 to 0.56 and 0.0195 to 0.0001) for GPP for developed land in ET and SC climate zones showed reasonable correlations each year (Table 4). In comparison, 50% of monthly GPP values were between 100 and 295, and 68 and 167 g C m<sup>-2</sup> mo<sup>-1</sup>, respectively, in ET and SC climate zones. Figure 11a shows a larger range of GPP in ET climate zone than SC climate zone.

**Table 4.** Coefficient of determination ( $\mathbb{R}^2$ ) and p-value (inside parentheses) for each land-use category

LAND-use -		GI	PP		NEE				
	2015	2016	2017	2018	2015	2016	2017	2018	
Developed land (ET, SC)	0.56 (0.0195)	0.70 (0.0006)	0.78 (0.0001)	0.63 (0.0022)	0.50 (0.0322)	0.62 (0.0024)	0.77 (0.0002)	0.57 (0.0045)	
Forestland (ET, TP)	0.67 (0.0068)	0.50 (0.0106)	0.33 (0.0501)	0.21 (0.1392)	0.81 (0.0009)	0.53 (0.0071)	0.17 (0.1813)	0.03 (0.5779)	
Shrub land (EP, TP)	0.95 (<0.0001)	0.68 (0.0010)	0.44 (0.0188)	0.75 (0.0003)	0.93 (<0.0001)	0.64 (0.0017)	0.20 (0.1435)	0.61 (0.0027)	
Cropland (HP, UC) Pastureland (ET, NC)	0.79 (0.0013) 0.95 (<0.0001)	0.69 (0.0008) 0.99 (<0.0001)	0.61 (0.0028) 0.61 (0.0026)	0.53 (0.0072) 0.76 (0.0002)	0.59 (0.0155) 0.94 (<0.0001)	0.45 (0.0178) 0.93 (<0.0001)	0.40 (0.0284) 0.45 (0.0170)	0.27 ( <b>0.0819)</b> 0.50 (0.0097)	
( , )	(	(	(	(	(	(		(	

![](_page_18_Figure_3.jpeg)

**Figure 11.** Box and Whisker plots of monthly (**a**) GPP distributions and (**b**) NEE distributions for five major land uses at each selected climate zone in the state of Texas. Note: C = cropland, F = forestland, P = pastureland, S = shrubland, and D = developed land. The white circles represent the mean, the solid horizontal lines represent the median, and gray circles represent outliers. Upper horizontal line = maximum, lower horizontal line= minimum, top of the box = upper quartile, bottom of the box = lower quartile, upper quartile to maximum = upper whisker, and the lower quartile to minimum = lower whisker.

Forestland of ET climate zone showed highest (255 g C m<sup>-2</sup> mo<sup>-1</sup>) and lowest (65 g C m<sup>-2</sup> mo<sup>-1</sup>) GPP in June 2015 and December 2018. Forestland in ET climate zone showed higher GPP during the summer between June and August each year except in 2017, when the highest GPP was observed in September and the lowest GPP in December of each year. Forestland of TP climate zone showed higher GPP during the summer from June to August except in 2016, when the highest and lowest GPP were observed in September and December (Figure 10b). Figure 11a shows a significantly different GPP distribution for forestland in ET climate zone than TP. Each summer, compared to other seasons, these climate zones received higher precipitation during the study period. However, the ET climate zone received more precipitation than the TP climate zone. In comparison, 50% of GPP in the ET climate zone was higher than 106 g C m<sup>-2</sup> mo<sup>-1</sup> and lower than 210 g C m<sup>-2</sup> mo<sup>-1</sup> whereas 50% of GPP in TP climate zone was lower than 111 g C m<sup>-2</sup> mo<sup>-1</sup> and higher than 35.5 g C m<sup>-2</sup> mo<sup>-1</sup>. Moreover, in comparison, the mean, median, and range of GPP in the TP climate zone were significantly different from those of the ET climate zone. However, R<sup>2</sup> values of 0.67 and 0.50 and *p*-values of 0.0068 and 0.0106, respectively, in 2015 and 2016 for forestland in two climate zones showed reasonable correlations, whereas the  $\mathbb{R}^2$  values of 0.33 and 0.21, and *p*-values of 0.0501 and 0.1392, respectively, in 2017 and 2018 for forestland in two climate zones showed poor correlations (Table 4).

Shrubland of EP climate zone showed higher GPP than shrubland of TP climate zone. However, both locations dominated by shrubland in these climate zones had similar seasonal variations in GPP (Figure 10c). These shrublands also had the highest GPP during the summer and lowest during the winter (Figure 10c). Both EP and TP climate zones had the highest GPP, respectively, 145 and 44 g C m<sup>-2</sup> mo<sup>-1</sup> in June 2015. Each summer, as compared to other seasons, these climate zones received slightly higher precipitation during the study period. However, the EP climate zone received slightly more precipitation than the TP climate zone. The R<sup>2</sup> values and *p*-values (0.95 to 0.68 and <0.0001 to 0.0010), for GPP for shrubland in EP and TP climate zones showed very good correlations each year except in 2017, when R<sup>2</sup> value and p-value were 0.44 and 0.0188, respectively (Table 4). Figure 11a shows a higher median and mean and larger range of GPP values in EP climate zone than TP climate zone.

Cropland of UC climate zone showed highest GPP during the summer of each year, which was more than double the HP climate zone (Figure 10d). For example, July 2015, June 2016, June 2017, and July 2018 showed the highest GPP values 355, 330, 373, and 366 g C m<sup>-2</sup> mo<sup>-1</sup> in the UC climate zone, respectively, whereas August 2015, September 2016, August 2017, and August 2018 showed the highest GPP values, respectively, 185, 162, 184, and 137 g C m<sup>-2</sup> mo<sup>-1</sup> in the HP climate zone, which had one to two months of time lag between the observed GPP peaks in two climate zones. Each summer, compared to other seasons, these climate zones received higher precipitation. However, the ET climate zone received more precipitation than the SC climate zone. The analysis showed an increasing trend of GPP from early April 2015, which continued to increase through the summer and decreased from June to December of each year. The lowest GPP (15–21 g C m<sup>-2</sup> mo<sup>-1</sup>) was observed in December of each year in both climate zones. Yet, the observed lowest GPP in the HP climate zone was lower than the UC climate zones by an average of 25 g C m<sup>-2</sup> mo<sup>-1</sup>. R<sup>2</sup> values and *p*-values from 2015 to 2018 (0.79 to 0.53 and 0.0013 to 0.0072) for GPP for cropland in HP and UC climate zones showed reasonable correlations each year (Table 4). Figure 11a shows higher median, mean, and larger range of GPP values in the UC climate zone than the HP climate zone.

Pasturelands of ET and NC climate zones showed higher GPP during summer and lower GPP during winter with a sharp change (from high to low) between July and August (Figure 10e). Since ET and NC climate zones share boundaries, and select grids were close to each other, both had similar seasonal variations of GPP. However, pastureland of the ET climate zone showed slightly higher GPP than the NC climate zone. Each summer except 2015, compared to other seasons, these climate zones received higher precipitation during the study period. However, the ET climate zone received slightly more precipitation than the NC climate zone. In addition, R<sup>2</sup> values and *p*-values (0.99 to 0.76 and <0.0001 to 0.0002) for GPP for shrubland in EP and TP climate zones showed excellent correlations

each year, except in 2017, when the R<sup>2</sup> value and p-value were 0.61 and 0.0226, respectively (Table 4). Figure 11a shows a higher median, and mean of GPP values in the ET climate zone than the NC, but both climate zones had similar ranges of GPP.

# 3.4.2. Temporal Distributions of NEE

Developed land-use of the ET climate zone showed higher monthly carbon emission and uptake compared to the SC climate zone (Figure 10f). Both climate zones had carbon emissions during the late fall and spring (November–April) and carbon uptakes during the summer and early fall (May–September). However, both climate zones had the highest carbon emissions and uptakes in a different month each year. For example, in 2015, ET and SC climate zones had the highest carbon emission, respectively, in April and March, whereas the highest carbon uptake was, respectively, in July and October/December (two peaks). Both climate zone showed slightly different median, and mean NEE (Figure 11b). However, the ET climate zone had larger NEE range than the SC climate zone. Additionally, NEE of developed land in the ET and SC climate zones showed slightly better correlations in 2016 and 2017 than in 2015 and 2018 (Table 4).

Forestland of the ET and TP climate zones showed the highest carbon uptake, respectively, in July 2015 and August 2017 (Figure 10g). Forestland of the ET climate zone had higher carbon uptake every year than the TP climate zone except in 2017. In August 2017, the TP climate zone had NEE of  $-71.4 \text{ g C m}^{-2} \text{ mo}^{-1}$  and the ET climate zone had NEE of  $-51.7 \text{ g C m}^{-2} \text{ mo}^{-1}$ . While forestlands of ET and TP climate zones showed some similarity in the temporal distribution of NEE (highest carbon uptake during summer in both zones), TP had very low carbon emission every year (0.4 to  $1.4 \text{ g C m}^{-2} \text{ mo}^{-1}$ ) except in May 2017, when this zone had NEE of  $22.4 \text{ g C m}^{-2} \text{ mo}^{-1}$ . Forestland of the TP climate zone had a smaller NEE range than forestland in the ET climate zone (Figure 11b). In comparison, mean, and range of NEE in TP climate zone were significantly different than the ET climate zone. The NEE median was close to each in both climate zones. R<sup>2</sup> values of 0.81 and 0.53 and *p*-values of 0.0009 and 0.0071 in 2015 and 2016 for NEE for forestland in two climate zones showed very good correlations, and R<sup>2</sup> values of 0.17 and 0.03, and *p*-values of 0.1813 and 0.5779 in 2017 and 2018 for NEE for forestland in two climate zones showed poor correlations (Table 4).

Shrublands of EP and TP climate zones showed similar seasonal variations in carbon emission and uptake during the study period (Figure 10h). However, the EP climate zone dominated by shrubland had slightly higher carbon emission than the TP climate zone. Similarly, it had a slightly higher carbon uptake than the TP climate zone in 2015–2016 and lower in 2017–2018. The ET climate zone had the highest carbon emission (18.3 g C m<sup>-2</sup> mo<sup>-1</sup>) in March 2018, and the TP climate zone had the highest carbon emission (12.6 g C m<sup>-2</sup> mo<sup>-1</sup>) in May 2018. On the other hand, the highest carbon uptake in EP ( $-43.3 \text{ g C m}^{-2} \text{ mo}^{-1}$ ) and TP ( $-32.4 \text{ g C m}^{-2} \text{ mo}^{-1}$ ) climate zones were observed in April 2015. R<sup>2</sup> values and *p*-values (0.93 to 0.61 and <0.0001 to 0.0027) showed very good correlations for NEE for shrubland in EP and TP climate zones each year except in 2017, when R<sup>2</sup> value and p-value were 0.20 and 0.1435 (Table 4). Both zones showed similar means and medians of NEE. However, the shrubland at the EP climate zone showed larger NEE range than the TP climate zone (Figure 11b).

Cropland of both climate zones showed higher carbon uptakes and emissions, respectively, during the summer and winter. However, cropland of the UC climate zone had more than double carbon emission and uptake during the peak of the year. For example, in 2015, the UC climate zone had the highest carbon uptake  $(-130.5 \text{ g C m}^{-2} \text{ mo}^{-1})$  in July, whereas the HP climate zone had the highest carbon uptake  $(-52 \text{ g C m}^{-2} \text{ mo}^{-1})$  in August (Figure 10i). R<sup>2</sup> values and *p*-values from 2015 to 2018 for NEE for cropland in HP and UC climate zones (0.59 to 0.27 and 0.0155 to 0.0819) showed good to poor correlations (Table 4). Figure 11a shows similar medians and means, but a larger range of GPP values in UC climate zone than HP climate zone. The primary y-axis has GPP and NEE (g C m<sup>-2</sup> mo<sup>-1</sup>) on the left and average monthly temperature (°C) on the right.

Distributions of NEE for Pastureland in NC and ET climate zones were very similar. Both climate zones showed carbon uptake during the summer and carbon emission during the winter (Figure 10j).

Since ET and NC climate zones share boundaries, and the selected grids were close to each other, both locations showed similar seasonal variations of NEE. However, pastureland of the ET climate zone had a slightly higher carbon uptake and carbon emission than the NC climate zones. The highest carbon uptake was observed in 2015, which continued to decrease until 2018 in both climate zones. The carbon emissions were found to be continuously increasing from 2015 to 2018. In addition, R<sup>2</sup> values and *p*-values (0.94 to 0.93 and <0.0001) for NEE for shrubland in EP and TP climate zones showed excellent correlations in 2015 and 2016, whereas R<sup>2</sup> values and *p*-values (0.45 to 0.50 and 0.0170 to 0.0097) NEE for shrubland in EP and TP climate zones showed reasonable correlations in 2017 and 2018 (Table 4). Figure 11b shows a higher median and mean of NEE values at the NC climate zone than the ET, but the ET climate zone had a larger range of NEE than the NC.

## 4. Discussion

Quantitative comparison of carbon fluxes in different climate zones and ecoregions can explain how climate change impact GPP and NEE distributions of various land uses. This study showed GPP was gradually increasing when seasons became hotter and more humid (Figure 10a-e). Moreover, the spatial distribution of GPP was dependent on climate zones (Figure 7). Based on the qualitative analysis of the GPP distributions, some climate zones could be considered as "climate zones with high GPP" or "climate zones with low GPP." For example, the TP climate zone showed low GPP for most of the months except in May and June 2015, and August 2015 and 2018 (Figure 7). Forestland of ET climate zone showed highest GPP in most of the months except in May and June 2015 and 2018, August and September 2015, when cropland of UC climate zone had higher GPP than forestland of ET climate zone. In addition, the forestland of the ET climate zone had higher GPP than the TP climate zone during the study period. Forestland of ET climate zone had higher GPP than the TP climate zone because the ET climate zone had dense forests and received a higher amount of precipitation than that of TP climate zone. Moreover, ET climate zone was covered by two ecoregions, SCP in the east and ECTP in the west. SCP and ECTP ecoregions were dominated by forestland and pastureland, respectively. This study supports the finding of Ma et al. (2015) [69], who explained that forests always store much larger amounts of carbon than other terrestrial ecosystems.

TP climate zone was mostly covered by Chihuahuan Deserts (CD) ecoregion, which included desert valleys, plateaus, and wooded mountains and received the lowest amount of precipitation [70]. In contrast, the ET zone received the highest amount of precipitation after the UC climate zone. UC and ET climate zones showed highest GPP during the study period because they continuously maintained dense vegetation/forest and received higher precipitation most of the year than other climate zones. The humid UC was known to support well-vegetated wetlands dominated by grasses and other temperate-climate plants such as forests and shrubs. GPP values in the UC climate zone were high because the prevailing climatic condition supported well-vegetated cropland and prairies, which meant higher rates of photosynthesis [71]. GPP values in other climate zones varied according to seasons. For example, NC and EP climate zone showed low to average GPP during the study period. However, GPP distribution in the NC climate zone was slightly higher than the EP climate zone because the NC climate zone received more precipitation than the EP climate zone. TP and UC climate zones had the lowest and the highest GPP, respectively, which is consistent with the climate conditions, and the land uses in those zones.

Amount of precipitation, temperature, and wind speed, which characterize each climate zone, impact the productivities and types of land-use in the climate zone. Temperature, types of land-use, and precipitation played a significant role in the spatial distribution of GPP across the state. While ET and NC climate zones shared boundaries, pastureland in the ET zone showed higher GPP than the NC zone because ET had a more seasonal tropical climate, which supported increased aboveground biomass during spring and summer than NC (Figure 7). Since both selected pasturelands were in two different climate zones and their climatic conditions were slightly different, the dissimilarities between these locations could be attributed to their vegetation growth and characteristics.

While EP and TP climate zones shared boundaries, comparatively, the EP climate zone was more humid than the TP climate zone. Consequently, shrubland of EP zone had more GPP than the TP climate zone. However, shrubland in EP and TP climate zones showed large differences in GPP distribution during summer (June–August), although GPP distributions were similar from fall to winter (Figure 7). Their similarities could be attributed to the same vegetation while their differences could be attributed to differences in climate at the two locations.

Open-developed land, which also included trees, grasses, pastures, various infrastructures, etc., made it unique compared to other land uses in this study. Developed land in the ET climate zone showed low GPP ( $<100 \text{ g C m}^{-2} \text{ mo}^{-1}$ ) in December suggesting a significant impact of low precipitation and temperature, which could be responsible for the major decline in productivity. Seasonal climatic conditions in ET support vegetation's growth. These conditions do not occur consistently in SC climate zone. SC is rather known for its natural diversity, which included semi-arid ecosystems, sweeping grasslands, and swampy, humid bayous. However, GPP was found to be higher on land uses in such climate zones (e.g., ET), which experienced more frequent higher rainfall, higher temperature variations, and higher humidity.

Climatic conditions, types of land-use, and seasonal changes impacted the spatial distribution of NEE across the state. When NEE distributions of identical land-use were compared at two different climate zones, these climatic conditions showed a significant impact on the net ecosystem exchange. All climate zones showed carbon emission in December. However, UT and ET climate zones showed highest carbon emissions, and TP climate zone showed the lowest carbon emissions in December because the UC climate zone received more than double the precipitation during this month. During the summer, all of the climate zones showed carbon uptake except HP, LRP, and TP, which had carbon emission in some of the summer months in 2018. These could be due to the effect of intermittent seasonal rainfall and change in land-use, which were identified as environmental drivers that impact carbon exchange in an ecosystem, as well as temperature variations across the climate zones. In comparison, climate zones dominated by forest, pasture, and crop showed more carbon uptake from April to September each year except HP cropland and TP forestland, because these climate zones received a low amount of precipitation, had higher elevation and lower temperature.

Each climate zone showed a decreasing trend and smaller variability in annual GPP from 2016 to 2018. However, it showed higher annual variability in GPP between the climate zones. The humid climate zones located close to the coast and dominated by forest, pasture, and croplands, had higher annual GPP than the semi-arid climate zones dominated by shrub and croplands. Additionally, humid climate zones that had more developed lands showed larger spatial variability (SD) in annual GPP due to land-use heterogeneity.

The seasonal effects on NEE were different in the tropical ET, UC, NC, and SC climate zones than in semi-arid TP, HP, and parts of EP climate zones, which explains different effects of seasonal changes on NEE distributions at these climate zones. NEE distributions changed from carbon emission in April to carbon uptake by June, whereas carbon uptake in August was changed to carbon emission by December. It shows that a tropical wet climate enhances carbon uptake, whereas the arid climate enhances carbon emission.

East Texas, dominated by forestland and pastureland, showed a balance between seasonal variations in carbon emission and uptake, whereas other climate zones, dominated by other land uses (e.g., developed land, cropland) showed a poor balance between seasonal variations in carbon emission and carbon uptake. However, climate zones dominated by shrubland showed little or no carbon emission during the study period. These findings aligned with previous studies, which showed shrublands had more consistent carbon uptake than grass or pasturelands because of the longer growing season and lower ecosystem respiration, although they show similar productivity [72]. Shrublands of EP and TP climate zones had the smallest NEE variations among all of the locations. This could be due to a water deficit during winter, which caused a reduction in ecosystem respiration, and GPP tended to decline in an ecosystem as water supply reduced, changing the ecosystem from a

carbon source to sink [73]. In addition, each land-use and climate zone showed an increase in carbon emission or decrease in carbon uptake after the rain events. These findings support the previous studies, which showed  $CO_2$  dissolved in rainwater released when soil pore occupied by  $CO_2$  was replaced by rainwater [74].

Each climate zone showed a decreasing trend in annual NEE and transition from carbon uptake to carbon release from 2016 to 2018. However, it showed higher annual variability in NEE between the climate zones. The humid climate zones (UC, S, and SC) located close to the coast and dominated by forest, pasture, and croplands, showed an annual balance of carbon uptake from 2016 to 2018 except LV climate zone, which had an annual balance of carbon uptake from 2016 to 2017 and annual balance of carbon release in 2018. All other climate zones (HP, LRP, NC, ET, TP, and EP) showed an annual balance of carbon uptake from 2016 to 2018. In 2017, hurricane Harvey could have some impact in UC, SC, and S climate zones, which caused annual balance of carbon uptake until 2018.

Change in spatial coverage of particular NEE and GPP ranges between selected months of 2018 and 2015 showed more GPP production in some parts of the state and less in others (Table 2). The reason for the low or high range of GPP and NEE values in any year in a climate zone of the state could be attributed to the types of vegetation and climate variability associated with the climate zone and ecoregion or the location. The study showed select land uses of two climate zones had significantly different temporal GPP and NEE distributions except for pasturelands of NC and ET climate zones (Figure 11). Quantitatively, the majority of land uses had a smaller range of GPP (119–213 g C m<sup>-2</sup> mo<sup>-1</sup>) and NEE (62–149 g C m<sup>-2</sup> mo<sup>-1</sup>) except developed land of ET, cropland of UC and shrubland of TP climate zones. Developed land of ET climate zone had the largest GPP range (362 g C m<sup>-2</sup> mo<sup>-1</sup>), and NEE (240 g C m<sup>-2</sup> mo<sup>-1</sup>) and shrubland of TP climate zone had the smallest GPP range (80 g C m<sup>-2</sup> mo<sup>-1</sup>) and NEE (45 g C m<sup>-2</sup> mo<sup>-1</sup>). The large variations in GPP and NEE for different land-use and climate zones indicated that the climate variability and land-use change, in combination, have a significant impact on GPP, carbon emissions, and carbon uptakes (Figure 11). The analysis showed that increased GPP and NEE during the summer and winter tended to be compensated by the reduced GPP and NEE during the winter and summer, respectively, resulting in little or no change in annual GPP and NEE. GPP peaked during summer and was lowest in winter, whereas NEE had the highest carbon uptake in summer and highest carbon release in winter.

Overall, the study showed a significant impact of climate and land-use change on the spatial and temporal distributions of GPP and NEE across Texas. Moreover, cropland, forestland, and shrubland showed more carbon uptake than carbon emission, which can help in soil carbon sequestration.

# 5. Conclusions

It is important to understand the changes in gross primary productivity (GPP) and net ecosystem exchange (NEE) under changing climate and land-use change. This study used soil moisture active and passive (SMAP) Level 4 carbon products to quantify spatial and temporal distributions and changes of GPP and NEE for selected terrestrial ecosystems across Texas. The SMAP's carbon products were compared and analyzed for monthly, and annual measurements of GPP and NEE for five land uses and ten locations from seven climate zones during the study period.

This study used EC (GPP and NEE) measurements from one location of the study area to evaluate the performance of SMAP (GPP and NEE) estimates at daily and monthly time scales. However, it should be recognized that no other EC NEE measurements were available to evaluate across Texas during the study period.

This study revealed significant effects of climate and land-use change on spatial and temporal distributions of GPP and NEE in Texas. Results showed that the carbon net exchange rates vary with the climate and land-use change across Texas. While the same land-use at two different climate zones had a different rate of NEE and GPP, different land uses within the same climate zone had different

net ecosystem exchanges and productivity rates. Carbon dioxide fluxes at the selected locations were found to be impacted by both climatic conditions and land-use change.

GPP and NEE distributions showed high  $CO_2$  exchange at locations with a significant amount of frequent rainfall, higher temperature, and dense vegetation, because these factors had a positive impact on the amount of organic matter input to soil carbon. For example, croplands had higher GPP and NEE in the UC climate zone but a lower value in the HP climate zone. However, climatic conditions were found to have a lesser impact on  $CO_2$  exchange at some land uses like pastureland and shrubland. These land uses showed a minor increase in  $CO_2$  flux even under similar climatic conditions compared to croplands or forestlands. GPP and NEE fluxes showed strong seasonality under the influence of temperature, precipitation, and land-use in each climate zone.

While the eddy covariance method made it possible to measure NEE with precision and contributed to the identification of the characteristics of carbon emission/uptake activities of various global ecosystems, there were few EC towers active in the state. Therefore, remotely sensed carbon products were very helpful to study the ecosystem. The limitation encountered in this study is the inability to cover all the land uses in the state, which would have provided a more robust analysis and possibly more accurate estimations of carbon productivity and net carbon exchange.

Further, it is recommended to evaluate SMAP carbon products in different climate zones and land-use categories using in-situ measurements. It is also recommended to conduct further research by including SMAP soil organic carbon (SOC) and soil heterotrophic respiration (Rh) to quantify terrestrial components of the carbon cycle in the Texas environment.

Finally, this study provides useful information on the terrestrial carbon cycle, which is important for understanding the global carbon cycle, carbon resource management, and carbon sequestration.

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