


Article

Is Drought Increasing in Maine and Hurting Wild Blueberry Production?

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Abstract: A few severe drought events occurred in the Northeast (NE) USA in recent decades and caused significant economic losses, but the temporal pattern of drought incidents and their impacts on agricultural systems have not been well assessed. Here, we analyzed historical changes and patterns of drought using a drought index (standardized precipitation-evapotranspiration index (SPEI)), and assessed drought impacts on remotely sensed vegetation indices (enhanced vegetation index (EVI) and normalized difference vegetation index (NDVI)) and production (yield) of the wild blueberry fields in Maine, USA. We also analyzed the impact of short- and long-term water conditions of the growing season on the wild blueberry vegetation condition and production. No significant changes in the SPEI were found in the past 71 years, despite a significant warming pattern. There was also a significant relationship between the relatively long-term SPEI and the vegetation indices (EVI and NDVI), but not the short-term SPEI (one year). This suggests that the crop vigor of wild blueberries is probably determined by water conditions over a relatively long term. There were also significant relationships between 1-year water conditions (SPEI) and yield for a non-irrigated field, and between 4-year-average SPEI and the yield of all fields in Maine. The vegetation indices (EVI and NDVI) are not good predictors of wild blueberry yield, possibly because wild blueberry yield does not only depend on crop vigor, but also on other important variables such as pollination. We also compared an irrigated and a non-irrigated wild blueberry field at the same location (Deblois, Maine) where we found that irrigation decoupled the relationship between the SPEI and NDVI or EVI.

Keywords: wild blueberry barrens; temperature; precipitation; drought index (SPEI); drought impact; normalized difference vegetation index (NDVI); enhanced vegetation index (EVI)



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1. Introduction

Elevated atmospheric temperatures, increased rainfall variabilities, and more frequent extreme drought events associated with anthropogenic climate change have been significantly damaging agricultural systems and crop production globally [1,2]. Additionally, local and microclimate changes could be more intense and significantly different compared to the reported average global or regional climate changes in terms of temperatures and precipitation [3–5]. For instance, a recent study on wild lowbush blueberry crops in Downeast, Maine (ME), USA has revealed that the summer temperatures of wild blueberry fields have been increasing significantly faster in the past forty years compared to that of the region (the state of Maine, Northeast (NE) USA) [6]. Such higher increasing temperature patterns in agricultural lands will exacerbate the impacts of drought events due to increased water loss [7,8]. Severe drought incidents have been reported in recent decades in NE USA and caused significant economic losses [9–11]. However, the historical trends of drought and their impacts on agricultural systems in this region have not been carefully assessed.

The wild blueberry (*Vaccinium angustifolium* Aiton) is one of the culturally and economically valuable crops in NE USA, which has been growing naturally for hundreds of

years at the coastal barrens of the state of Maine in the USA, Atlantic Canada, and the province of Quebec in Canada. It is quite a unique agricultural system, as ~1500 genetically distinct wild blueberry plants can be found in a large field (~5 ha) [12]. This crop grows in a two-year production cycle where the stems, leaves, and buds develop during the first year, referred to as a prune year, and those plants bloom and produce fruits during the second year, referred to as a crop year [12]. After harvesting the berries from the end of July to early August in a crop year, plants are pruned to the ground by mowing or burning and the crop cycle starts again the following prune year. It is still unknown how this unique wild agricultural system will respond to the unprecedented changes in rainfall patterns and decreasing soil moisture in this region [6,7]. In fact, the summer temperatures and, hence, potential evapotranspiration of the wild blueberry fields at Downeast, Maine have been increasing significantly in the past decades [6]. Yet, we do not know whether wild blueberry fields experienced drought stress over the years, not to mention we do not have any scientific evidence of how this crop has been responding to drought incidents over the years. Although some controlled drought experiments revealed that wild blueberry plants are drought tolerant based on one growing cycle (2 years) [13,14], we still do not know whether drought has short-term and long-term effects on the vigor and production of this crop. Hence, the historical drought patterns that the wild blueberry barrens have been experiencing, and their impacts on crop vigor and production, need to be analyzed to guide management practices in the future.

Drought has been a great threat to the agricultural systems worldwide, and has been extensively studied in different regions on varieties of crops [15,16]. Droughts in agricultural lands are related to a lack of precipitation and inadequate water supply to crops. In order to analyze drought severity, several meteorological drought indices have been developed based on different combinations of precipitation, temperature, soil moisture availability, and vegetation conditions. Widely used drought indices include the Palmer Drought Severity Index (PDSI) [17], the standardized precipitation index (SPI) [18], and the standardized precipitation-evapotranspiration index (SPEI) [19]. Here, in order to analyze historical drought patterns for wild blueberry fields in Maine, we adopted the SPEI over other drought indices as it is determined based on precipitation, temperature, and potential evapotranspiration [19]. Moreover, the SPEI would be the most useful index to determine the water conditions (dry/wet) and drought severity of an agricultural system during both the short period and long period [19,20]. This is because the SPEI's multi-scalar character enables it to detect, monitor, and analyze droughts more effectively, as it can quantify the water conditions (dry/wet) and the drought severity according to its duration and intensity [19]. The SPEI also allows the comparison of drought severity through time and space, since it can be calculated over a wide range of climates.

Besides determining the historical drought patterns for the wild blueberry barrens, we also assessed the impacts of drought and water conditions on the crop vigor and production of wild blueberries over the years. In order to determine the crop vigor, which could be indicated by their greenness and biomass, widely used remotely sensed vegetation indices such as the normalized difference vegetation index (NDVI) and the enhanced vegetation index (EVI) were used to analyze the vegetation condition of wild blueberry fields and their response to historical drought incidents. The NDVI and EVI are widely used to assess vegetation health and biomass production, as they represent a composite property of canopy cover, canopy structure, canopy greenness, leaf area, and chlorophyll content [6,21–24]. Moreover, we analyzed the effects of short- and long-term water conditions (or water deficits; indicated by the SPEI) on the wild blueberry crop vegetation status and production in Maine, and the impacts of irrigation in alleviating drought effects and securing production. Our study will provide a complete understanding of how this crop has been affected by frequent erratic changes in rainfall and drought.

Therefore, the objectives of this study were:

1. To test whether drought incidents and severity were increasing in the past 71 years by analyzing the historical changes in temperature, precipitation, and drought index (SPEI),

as well as the changing pattern of the EVI and fruit production of wild blueberry fields in the past two decades in the study sites of the major wild blueberry production region of Maine, USA.

2. To determine the impacts of drought on the vegetation condition and production of the wild blueberry crops in Maine by establishing relationships among the drought index (SPEI), vegetation indices (NDVI and EVI), and yield.

3. To test whether irrigation alleviated the impacts of drought on the vegetation health and production of the wild blueberry crops in Maine by comparing nearby irrigated and non-irrigated fields.

2. Materials and Methods

2.1. Study Area

We analyzed the wild blueberry fields in Maine, USA as a whole, and two specific fields with a good record of yield data (Figure 1). The wild blueberry fields in the major production region are located in the Washington and Hancock counties of Maine (referred to as “Maine WB Fields”, Figure 1a,b). The two specific fields selected were the Airport wild blueberry field at Deblois, Maine (referred to as “Airport”, Figure 1c), and the Baxter wild blueberry field at Deblois, Maine (referred to as “Baxter”, Figure 1c). The soil of the wild blueberry fields in Maine is well-drained sandy loam acidic soil [25]. The studied region has a four-season climate with an average annual minimum temperature of -10.6°C and a maximum temperature of 24.2°C , and monthly average precipitation as low as 85.1 mm and as high as 136.4 mm [26].

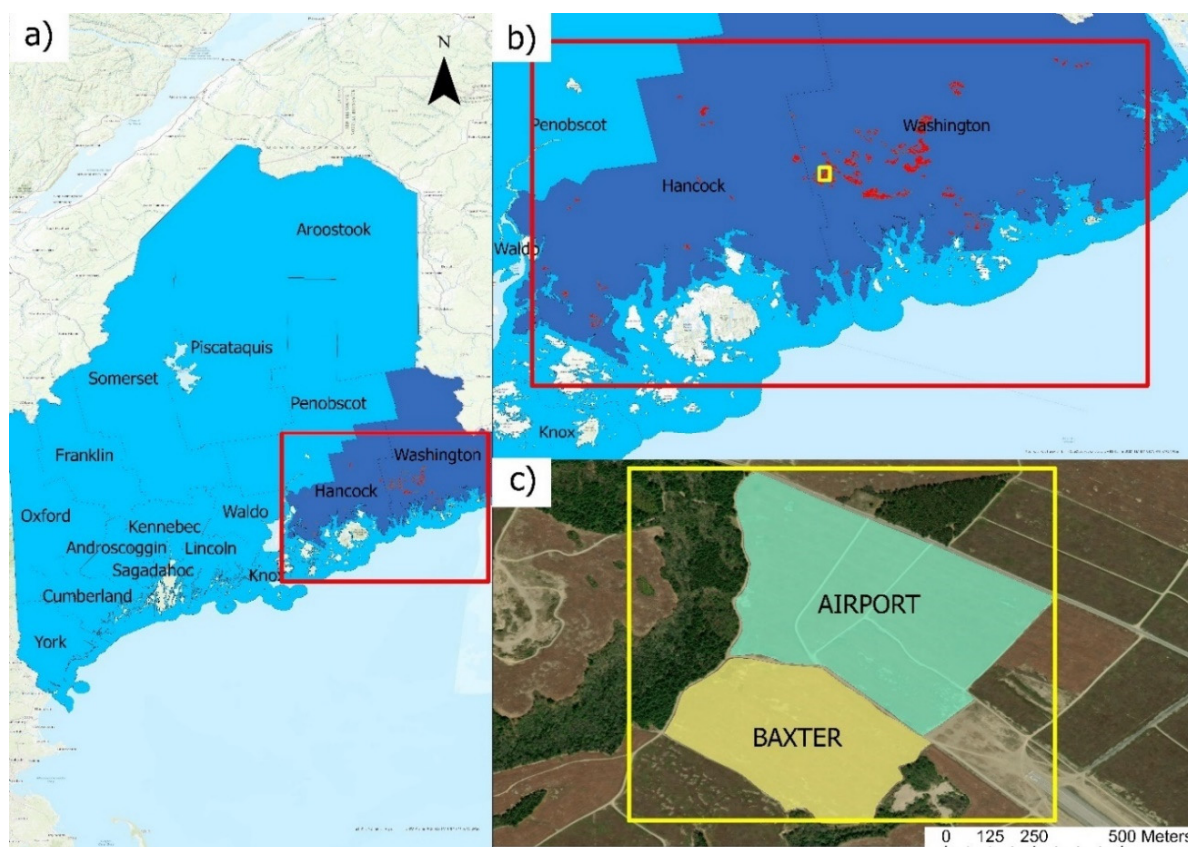


Figure 1. Location of the study sites: (a) a map of the state of Maine (light blue color), USA showing the location of the major wild blueberry production region (Washington and Hancock County) in dark blue color; (b) a map of the major wild blueberry production region in Maine showing 89 wild blueberry fields in red polygons for this study with an area of 0.06 km^2 ($250\text{ m} \times 250\text{ m}$) or larger; (c) Airport and Baxter wild blueberry fields of Wyman's in Deblois, Washington County, ME, USA.

2.1.1. Wild Blueberry Fields in Major Wild Blueberry Production Region of Maine, USA

Washington and Hancock counties together are the largest producer (~90%) of wild blueberries in Maine [27]. In this study, a total of 89 wild blueberry fields were considered, among which 69 fields were in Washington County, and 20 fields were in Hancock County (Figure 1a,b). Among all the wild blueberry fields of that region, 89 fields with 0.06 km² (250 m × 250 m) or larger areas were selected for this study. The land area threshold of 0.06 km² was used because the remote sensing data products that we used had a spatial resolution of 250 m. The selected wild blueberry fields are represented in red color in Figure 1a,b.

2.1.2. Airport and Baxter Wild Blueberry Fields in Deblois, Maine

The Airport and Baxter fields are adjacent to each other (Figure 1c). These two fields are part of the commercial blueberry fields owned by Jasper Wyman and Son in Deblois (longitude: −68.0001° N, latitude: 44.7350° W), Washington County, Maine, USA. In terms of agricultural management, these two fields are historically treated equally except for irrigation. The Airport field is irrigated during the growing season, whereas the Baxter field is non-irrigated. During the growing season from May to September, the Airport field was irrigated when needed with Nelson Full-Circle Impact sprinklers (Walla Walla, WA, USA) uniformly across the field. The irrigation system was set to ensure 0.5 to 1.0 inches of water supply per week by compensating natural precipitation. The area of the Airport field is 77 acres (0.31 km²), and the Baxter field is 39 acres (0.16 km²). These two fields were selected to understand and differentiate the effectiveness of current uniform irrigation practices in a single production region with the same climatic conditions.

2.2. Data Acquisition and Methodology

A Keyhole Markup Language Zipped (KMZ) file locating the wild blueberry fields of Maine was produced based on a field survey carried out by the University of Maine Cooperative Extension. The polygons of the 89 wild blueberry fields (area > 0.06 km²) in the major wild blueberry production region, Maine (Figure 1a,b) were acquired from the KMZ file. The Airport and Baxter field polygons were acquired from a KMZ file based on a field survey by Jasper Wyman & Son, Deblois, Maine.

In this study, the SPEI was used as a drought index, which is calculated based on precipitation, temperature, and potential evapotranspiration data. The SPEI was chosen over another popular drought index, the PDSI, because the PDSI has a fixed temporal scale (between 9–12 months), which prevents the understanding of drought severity on different temporal scales [28]. In addition, the SPEI was chosen over the widely used SPI because the SPI only considers precipitation data and does not include air temperature and evapotranspiration data, which could also significantly influence the understanding of drought impacts on agriculture [19]. The SPEI's multi-scalar character enables it to detect, monitor, and analyze droughts more effectively, as it can quantify the drought severity according to its duration and intensity [19]. The SPEI allows the comparison of drought severity through time and space, since it can be calculated over a wide range of climates. In this study, the SPEI data were collected from the readily available open access database "SPEI Global Drought Monitor" (<https://spei.csic.es/map/maps.html>, accessed on 10 July 2020) in netcdf format. The netcdf files containing the SPEI data were transferred to ArcGIS Pro Version 2.7 (ESRI, Redlands, CA, USA) to acquire the SPEI data for the study sites (Airport, Baxter, and major wild blueberry region of Maine) over 71 years from 1950 to 2020, using the zonal statistics tool in ArcGIS Pro (Figure 2). The SPEI data were acquired on different temporal scales ranging from 1 month (SPEI_1) to 48 months (SPEI_48). These data were provided on a per-pixel basis at a 4 km spatial resolution. The SPEI (SPEI_6 of September) of only the growing season (April–September) was considered in this study. SPEI_6 of September represents the water conditions of a growing season (April–September). To understand the long-term (multi-year) impact of water conditions on the vegetation indices (EVI and NDVI) and yield of wild blueberry crops, the average

SPEI (SPEI_6 of September) of two, three, and four consecutive years was also calculated. A positive SPEI value represents wet conditions, whereas a negative SPEI value indicates dry conditions.

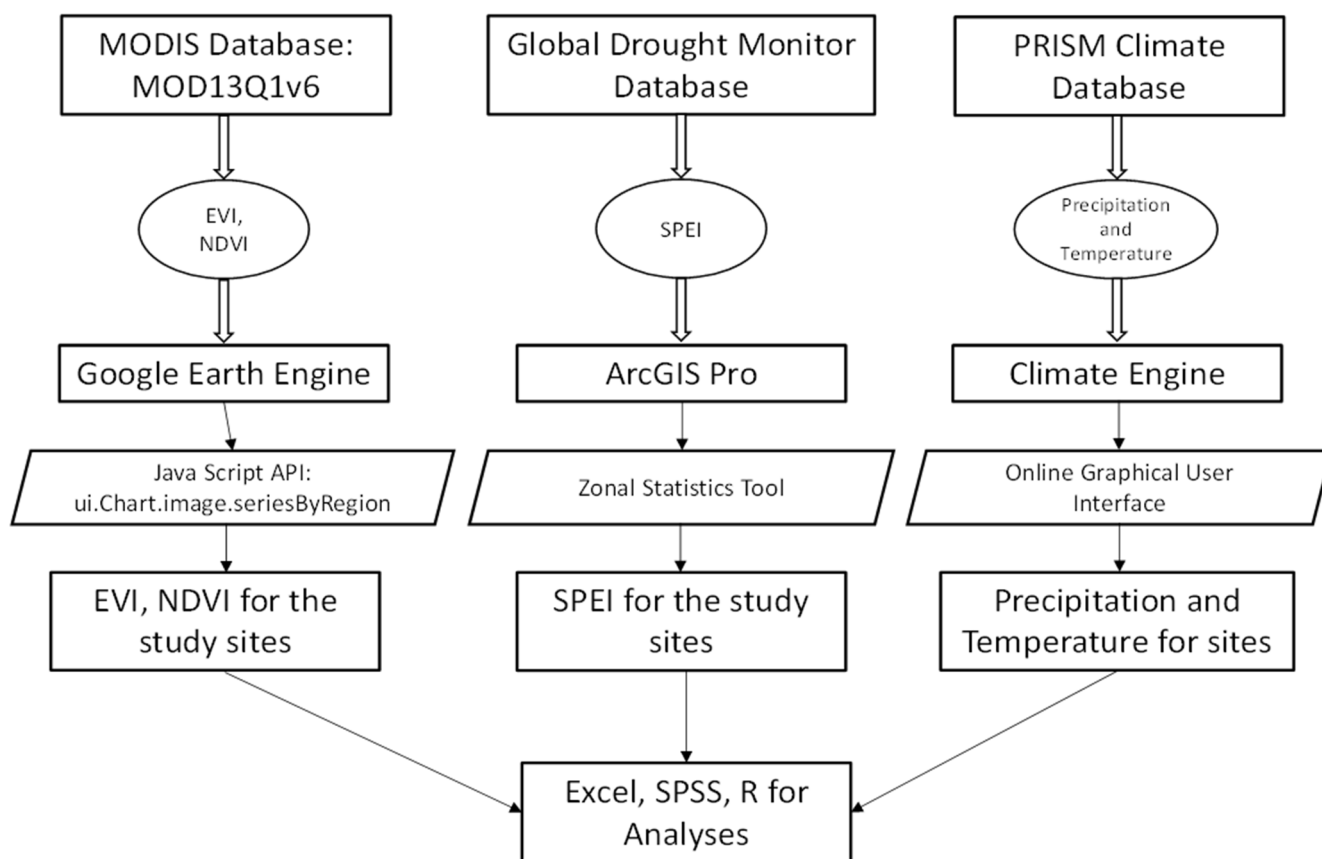


Figure 2. A flowchart showing the steps of data acquisition and analyses for this study.

The dataset of climate variables, such as total precipitation and mean temperature, during the growing season (May to September) over 71 years from 1950 to 2020 for the study sites (Airport/Baxter and the major wild blueberry region of Maine) was acquired from the online tool “Climate Engine” (<https://clim-engine.appspot.com/climateEngine>, accessed on 17 July 2021) of the Desert Research Institute, University of California, USA. Here, total precipitation refers to an average of monthly total precipitation (mm), and mean temperature refers to an average of the monthly mean air temperature at 2 m from the ground surface for the growing season. The original data sources for the climate variables were obtained from the AN81 m dataset of the PRISM Climate Group (<https://prism.oregon-state.edu/explorer/>, accessed on 17 July 2021). These data were provided on a per-pixel basis at a 4 km spatial resolution for the conterminous United States with a temporal resolution of one month (daily mean temperature and total precipitation were averaged monthly). This AN81 m dataset is available from January 1895. The extracted data were transferred into Microsoft Excel (Microsoft, Redmond, WA, USA) to calculate the average total precipitation and the mean temperature of the summer months (May to September) of each year (Figure 2).

In order to quantify vegetation responses to drought, satellite-based remotely sensed EVI and NDVI data for 21 years (2000 to 2020) of the studied wild blueberry fields were acquired from Google Earth Engine. These data were originally obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) product MOD13Q1 (<https://lpdaac.usgs.gov/products/mod13q1v006>, accessed on 25 July 2021). The MOD13Q1 dataset is preprocessed as well as readily and freely available. The MOD13Q1 Version 6 data

have a spatial resolution of 250 m, generated every 16 days. For the development of the MOD13Q1 product, an algorithm was used to select pixels with low clouds, low view angle, and maximum index value to obtain the best available pixels over the 16-day-period image acquisitions [29]. The MOD13Q1 product has two vegetation layers: NDVI and EVI. The NDVI is the most common one used for characterizing canopy leaf chlorophyll content based on the reflectance contrast between the red and the near-infrared (NIR) wavebands [30]. However, the NDVI has some limitations, such as (1) it saturates in dense vegetation, (2) it does not consider the canopy background noise, and (3) its ratioing properties to eliminate noise [31]. These limitations were improved in the EVI to some extent, and thus the EVI has several advantages over the NDVI as it has improved sensitivity over high biomass regions [31]. This dataset is readily available in the Google Earth Engine. The vegetation indices values over the summer months were extracted for the study sites using a JavaScript-based API in the Google Earth Engine (<https://code.earthengine.google.com/>, accessed on 25 July 2021) using the extraction command “ui.Chart.image.seriesByRegion”. The extracted data were transferred into Microsoft Excel (Microsoft, Redmond, WA, USA) to calculate the average EVI and NDVI of the summer months (May–September) of each year (Figure 2).

The historical yield data of Maine were collected from the United States Department of Agriculture (USDA), National Agricultural Statistics Service using a Quick Stats Ad-hoc Query Tool (<https://quickstats.nass.usda.gov/>, accessed on 26 July 2021). Historical yield data of the entire state of Maine (million lbs.) were available from 1924 to 2020, but the yield per production area data (lbs./acre) were only available from 2012 to 2020 (except 2013). It should be noted that the yield data were considered from all over the state of Maine, where ~90% of the yield was typically from the major wild blueberry production region (Washington and Hancock counties). The historical yield data of the Airport and Baxter fields at Deblois, Maine were provided by Jasper Wyman & Son, Maine. The yield (lbs./acre) data for the Airport and Baxter fields were available from 1993–2019 for every alternate year (except 2001 for the Baxter field).

2.3. Statistical Analysis

In this study, SPSS v23 (IBM Corp., Armonk, NY, USA), and RStudio software (RStudio, PBC, Vienna, Austria) were used for statistical analysis. Trend analyses of the climate variables (SPEI, Precipitation, Temperature) over the last 71 years (1950–2020) at the studied wild blueberry fields (Airport/Baxter and Maine) were conducted using a Mann–Kendall trend test and Sen’s slope estimator using the XRealStats (Addinsoft, New York, NY, USA) add-on in Microsoft Excel. The “pheno” package in RStudio was used to analyze the forward (UF) and backward (UB) curves of the sequential Mann–Kendall test statistics. Trend analyses of the EVI and yield over the last 21 years (2000–2020) at the studied wild blueberry fields (Airport/Baxter and Maine) were conducted using a Mann–Kendall trend test and Sen’s slope estimator using the XRealStats tool. To assess the statistical significance of the Mann–Kendall trend analysis, the significance level (α) was set to 0.05.

A Pearson correlation analysis was conducted between different temporal scales of SPEI and EVI and yield to understand the drought impact on vegetation (EVI) and yield at different temporal scales using SPSS v23. To assess the statistical significance of the Pearson correlation analysis, the significance level (α) was set to 0.05.

To understand the effects of short- to long-term water conditions (SPEI_1_Year to SPEI_4_Year) on the EVI and NDVI (average of the growing season: May–September) for the studied wild blueberry fields over 21 years (2000–2020), linear (in the form of $a + bx$) and non-linear (in the form $a + bx + cx^2$) regression analyses were also conducted using SPSS v23. A similar analysis was conducted to understand the short- to long-term impact of water conditions (indicated by SPEI_1_Year to SPEI_4_Year) on the yield of the studied wild blueberry fields. We determined the statistical significance of the relationship using the coefficient of determination and its significance (α) at $p < 0.05$.

3. Results

3.1. Historical Changes in SPEI, Climate Variables, EVI, and Productivity of Wild Blueberry Systems in Maine, USA

During the last 71 years (1950–2020), the drought index (SPEI, Figure 3a,b) and precipitation (Figure 3c,d) tended to increase marginally (Figure 4a–d; Table 1) in the studied wild blueberry fields in Maine (Figure 3a,c and Figure 4a,c), as well as in two specific fields (Airport/Baxter) at Deblois, Maine (Figure 3b,d and Figure 4b,d). However, the mean atmospheric temperature increased significantly in the wild blueberry fields in Maine overall (Figure 3e,f; Table 1), and in the two fields in Deblois, ME. These patterns were also supported graphically by the upward UF curve (forward trend) mostly being >0.0 and UB (backward trend) curve mostly being <0.0 (Figure 4e,f).

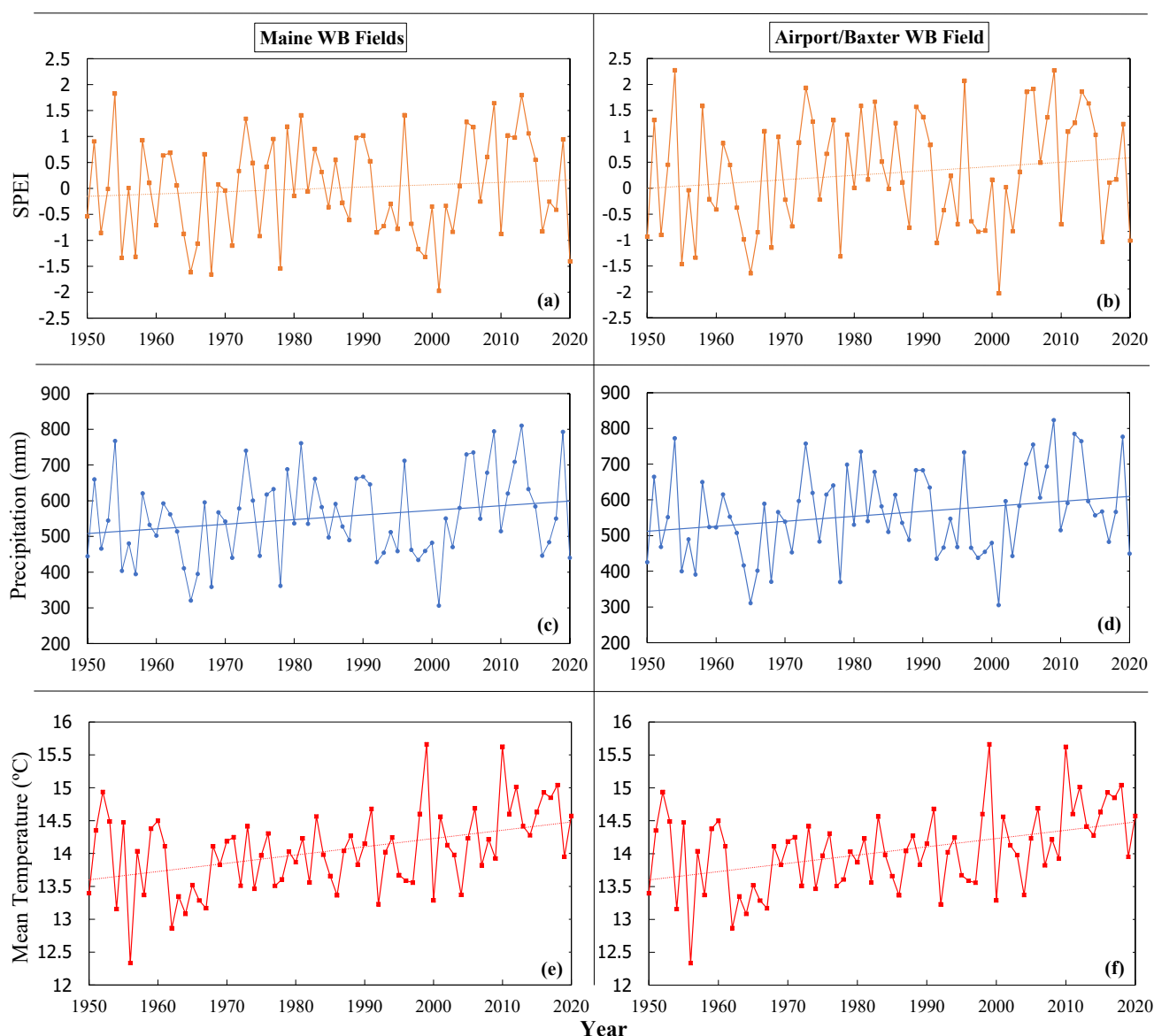


Figure 3. Historical (1950 to 2020) patterns of the (a,b) SPEI₆ of September; (c,d) mean precipitation (average of May–September); (e,f) average temperature (average of May–September) throughout the major wild blueberry production region in Maine as well as at the Airport/Baxter wild blueberry fields in Deblois, ME. A positive SPEI value represents wet conditions, while a negative SPEI value indicates dry conditions. Here, mean precipitation refers to an average of the monthly total precipitation (mm), and mean temperature refers to an average of the monthly air temperature at 2 m from the surface for the growing season.

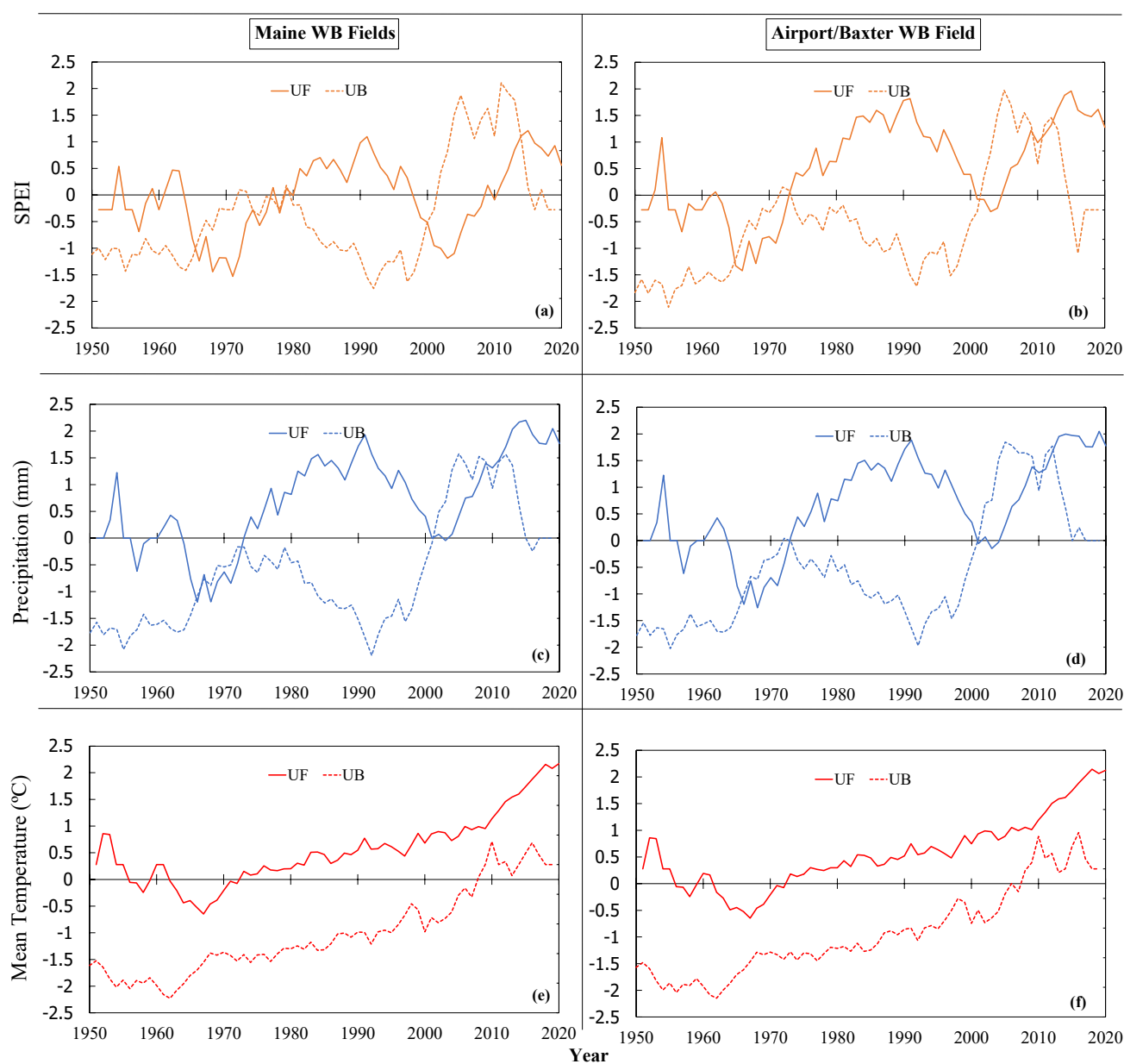


Figure 4. Sequential Mann–Kendall test statistics (UF and UB values) calculated from the (a,b) SPEI₆ of September; (c,d) mean precipitation (average of May–September); (e,f) average air temperature (average of May–September) throughout the major wild blueberry production region in Maine, as well as at the Airport/Baxter wild blueberry fields in Deblois, ME. Here, the upward UF curve (forward trend) mostly being > 0.0 , UB (backward trend) curve mostly being < 0.0 , and UF and UB not intersecting with each other indicate the significant increasing trends of the mean temperature. The intersections of the curves with the 0.0 line as well as with each other represent the non-significant changing (increasing/decreasing) trends of the SPEI and precipitation.

Based on the yield data from the crop years (every alternate year from 1993–2019), the wild blueberry yield of the Airport field (irrigated) had no significant change (Figure 5a; Table 2). No significant changes in the EVI during the growing season (April–September) of the Airport field were detected over the last 21 years (2000–2020) (Figure 5d; Table 2). In contrast, both the yield (Figure 5b) and the EVI (Figure 5e) showed significant increments in the Baxter field (non-irrigated; Table 2). No significant changes in yield were observed from the studied wild blueberry fields of Maine over the last 21 years (2000–2020) (Figure 5c). A significant increase in the EVI during the growing season (April–September) was observed over the last 21 years for fields of Maine as a whole (Figure 5f; Table 2).

Table 1. Sequential Mann–Kendall trend analysis of the standardized precipitation-evapotranspiration index (SPEI), precipitation and mean temperature (T_{mean}) at different wild blueberry study zones: Airport/Baxter wild blueberry fields (Deblois, ME), and Maine wild blueberry fields (Washington and Hancock counties, ME). Here, the SPEI refers to SPEI_6 of September. It represents the SPEI of the growing season (April–September) and indicates water conditions and drought severity. T_{mean} represents the average air temperatures during the growing period (May–September).

Mann–Kendall Test	Maine WB Fields			Airport/Baxter, Deblois, ME Irrigated/Non-Irrigated		
	SPEI	Precipitation	T_{mean}	SPEI	Precipitation	T_{mean}
Kendall's Tau	0.062	0.144	0.276	0.114	0.144	0.270
Mann–Kendall Stat (S)	153.000	357.000	687.000	283.000	359.000	671.000
Var (S)	40,588.33	40,588.33	40,588.33	40,588.33	40,588.33	40,588.33
<i>p</i> -value (two-tailed)	0.45	0.07	0.001	0.16	0.07	0.001
Alpha	0.05	0.05	0.05	0.05	0.05	0.05
Trend	Increasing (Non-significant)	Increasing (Non-significant)	Increasing (Significant)	Increasing (Non-significant)	Increasing (Non-significant)	Increasing (Significant)
Sen's Slope Q	0.005	1.344	0.013	0.008	1.304	0.012

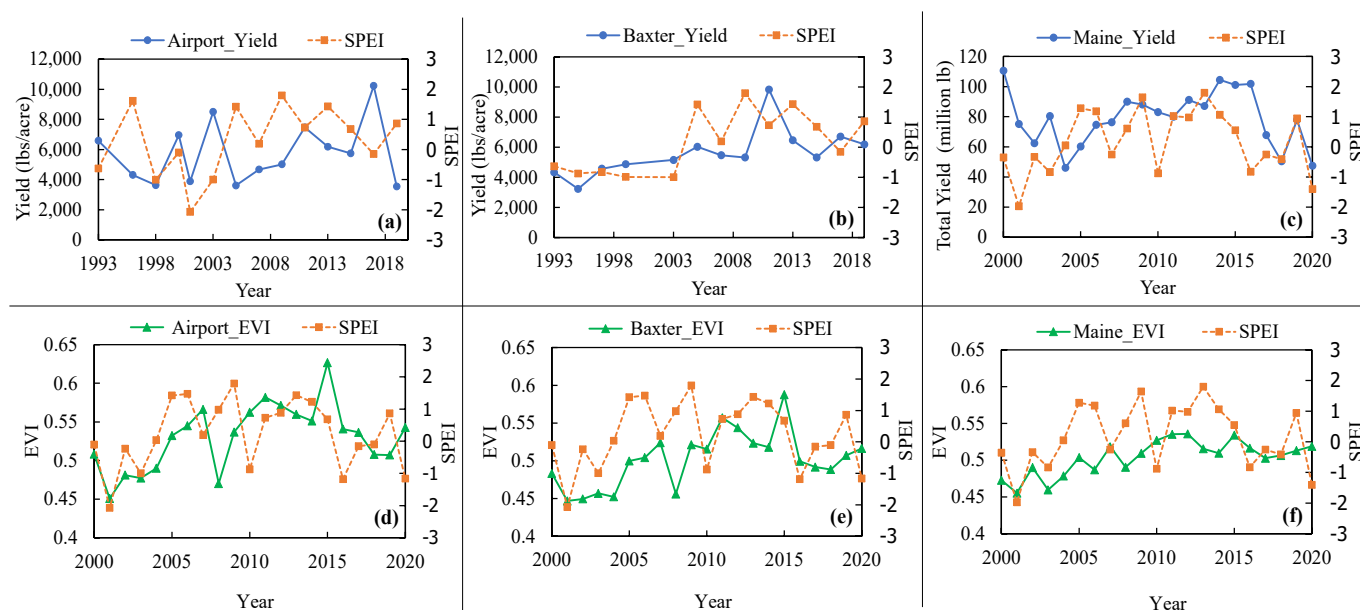


Figure 5. (a,d) Historical values of yield and SPEI ((a): 1993–2019), and of the EVI and SPEI ((d): 2000–2020) for the Airport (irrigated) field, Deblois, ME. (b,e) Historical values of yield and SPEI ((b): 1993–2019), and in the EVI and SPEI ((e): 2000–2020) for the Baxter (non-irrigated) field, Deblois, ME. (c,f) Historical values of yield and SPEI ((c): 2000–2020), and in the EVI and SPEI ((f): 2000–2020) for the major wild blueberry production region in Maine. Here, orange dashed lines indicate SPEI, blue solid lines indicate yield, green solid lines indicate EVI. Here, SPEI refers to SPEI_6 of September. It represents the SPEI of the growing season (April–September) and indicates water conditions. A positive SPEI value represents wet conditions, while a negative SPEI value indicates dry conditions.

Table 2. Sequential Mann–Kendall trend analysis of yield and enhanced vegetation index (EVI) at three different wild blueberry study zones: Airport (irrigated field, Deblois, ME), Baxter (non-irrigated field, Deblois, ME), and Maine wild blueberry fields (Washington County and Hancock County, ME).

Mann–Kendall Test	Airport, Deblois, ME (Irrigated Field)		Baxter, Deblois, ME (Non-Irrigated Field)		Maine WB Fields	
	Yield	EVI	Yield	EVI	Yield	EVI
Kendall’s Tau	0.099	0.257	0.667	0.333	0.057	0.476
Mann–Kendall Stat (S)	9.000	54.000	52.000	70.000	12.000	100.000
Var (S)	333.667	1096.667	268.667	1096.667	1096.667	1096.667
<i>p</i> -value (two-tailed)	0.667	0.110	0.002	0.037	0.740	0.003
Alpha	0.050	0.050	0.050	0.050	0.050	0.050
Trend	Increasing (non-significant)	Increasing (non-significant)	Increasing (significant)	Increasing (significant)	Increasing (non-significant)	Increasing (significant)
Sen’s Slope Q	54.10	0.003	89.91	0.003	0.301	0.003

3.2. Relationships between SPEI and Vegetation Indices in Wild Blueberry Fields of Maine

Based on the relationships of both the short-term and long-term average SPEI with the EVI and NDVI (Figures 6 and 7, and Table S1), the long-term SPEI showed a stronger influence on the vegetation indices (EVI in Figure 6 and NDVI in Figure 7) of wild blueberries compared to the short-term SPEI. While analyzing the impact of the short-term SPEI (SPEI_1_Year in Figures 6 and 7, and SPEI_1 to SPEI_11 in Table S1) on the EVI (Figure 6a–c) and NDVI (Figure 7a–c) during the growing season (May–September), no significant relationship was observed for the studied wild blueberry fields in Maine.

On the contrary, while observing the impact of the long-term SPEI (2 to 4 consecutive years) on both the EVI and NDVI of the wild blueberry fields during the growing season, we found both significant linear and quadratic relationships between the SPEI and the EVI (Figure 6d–l) as well as between the SPEI and the NDVI (Figure 7d–l). Among the significant linear and quadratic relationships between an average SPEI of 2 consecutive years (SPEI_2_Year) and vegetation indices for the Airport (Figures 6d and 7d), Baxter (Figures 6e and 7e), and studied wild blueberry fields in Maine (Figures 6f and 7f), the coefficient of determination (R^2) was higher for the quadratic relationships. Moreover, the strength (R^2 values) of both the linear and quadratic relationships was higher when considering more consecutive years, such as SPEI_3_Year (Figures 6g–i and 7g–i) and SPEI_4_Year (Figures 6j–l and 7j–l) compared to the SPEI_2_Year (Figures 6d–f and 7d–f). Although both the relationships between the SPEI and EVI (Figure 6) as well as the SPEI and NDVI (Figure 7) were significant when considering the long-term SPEI, the coefficient of determination (R^2) was higher for the relationships between the SPEI and EVI compared to the relationships between the SPEI and NDVI. Because of the stronger relationship between the SPEI and EVI, we further analyzed the impact of the short- and long-term water conditions (SPEI) on wild blueberry yield, as well as the influence of monthly water conditions (SPEI) during the growing season on EVI and yield. Interestingly, when considering the impact of the monthly SPEI (different temporal SPEI in Table S1) during the growing season, the SPEI of the early season (April–June) showed more impacts on the EVI of the wild blueberry fields compared to the SPEI later in the season (July–August).

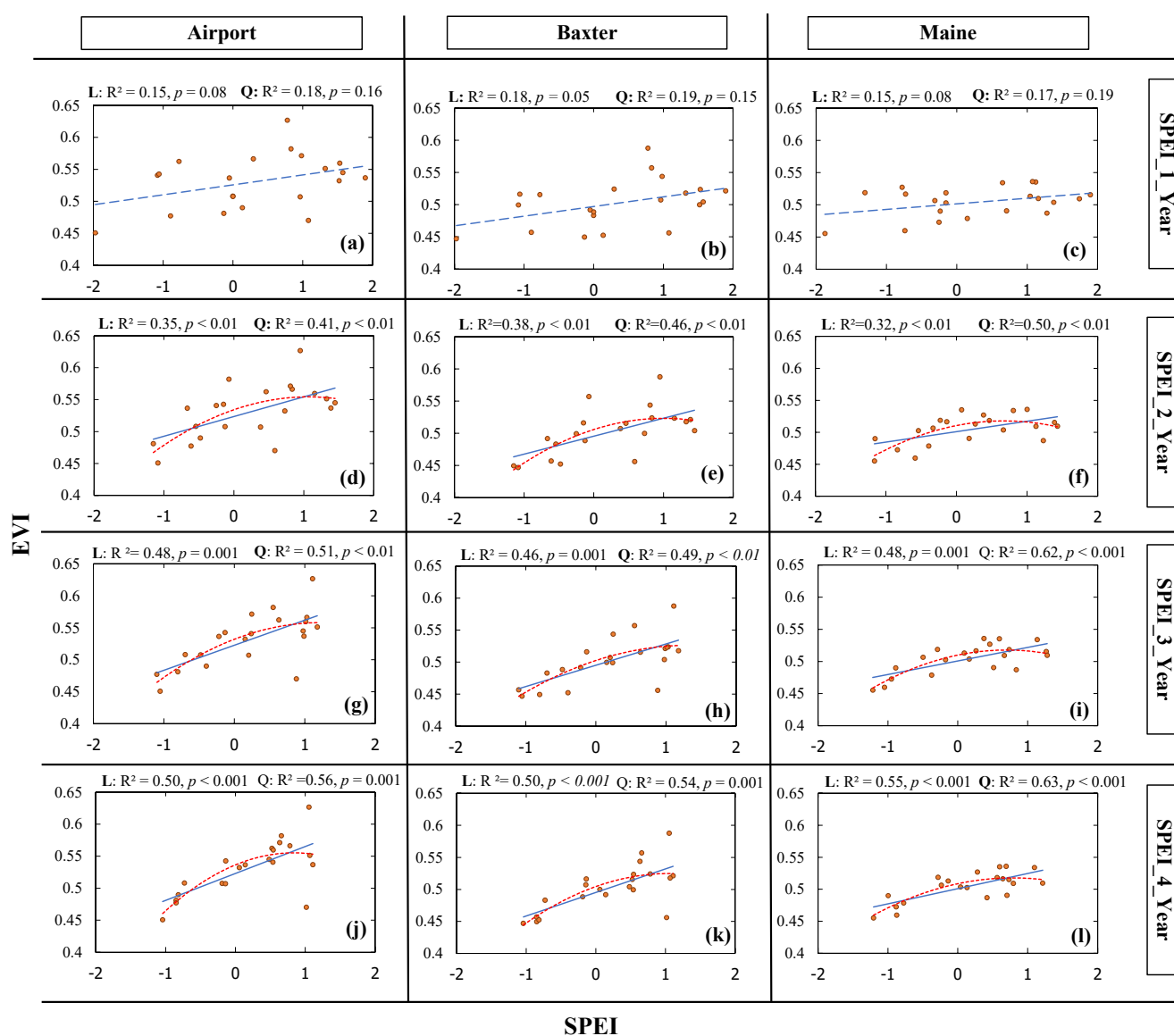


Figure 6. Average enhanced vegetation index (EVI) of wild blueberry fields during the growing season (May to September) for three different study zones: Airport (irrigated), Baxter (non-irrigated), and the major wild blueberry production region in Maine in relation to (a–c) SPEI_1_Year; (d–f) SPEI_2_Years (average SPEI of two consecutive years); (g–i) SPEI_3_Years (average SPEI of three consecutive years); (j–l) SPEI_4_Years (average of SPEI of four consecutive years). Here, SPEI refers to SPEI_6 of September and it represents the SPEI (water conditions) of the growing season (April–September). A positive SPEI value represents wet conditions, while a negative SPEI value indicates dry conditions. The blue solid lines indicate significant ($p < 0.05$) and blue dashed lines indicate marginally significant ($p < 0.10$) linear relationships. The dashed red lines indicate significant ($p < 0.05$) or marginally significant ($p < 0.10$) quadratic relationships. The time period of the EVI and SPEI data was from 2000 to 2020.

3.3. Relationships between SPEI and Yield of Wild Blueberry Fields in Maine

The impacts of the short-term and long-term SPEI on the wild blueberry yield (Figure 8 and Table S2) were different from the relationships between the SPEI and EVI during the growing season (April–September) (Figure 6 and Table S1). A significant and positive linear relationship was found between the short-term SPEI (SPEI_1_Year) and yield for the non-irrigated Baxter field (Figure 8b), whereas the relationship between the short-term SPEI (SPEI_1_Year) and yield was non-significant at the 95% confidence level (marginally significant at the 90% confidence level, $p = 0.058$) for the irrigated Airport field (Figure 8a). For the wild blueberry fields in Maine as a whole, we found a marginally significant ($p < 0.1$)

and positive linear relationship between the short-term drought index (SPEI_1_Year) and the wild blueberry yield (Figure 8c). We found a significant quadratic relationship between the short-term SPEI (SPEI_1_Year) and yield for the non-irrigated Baxter field (Figure 8b), but not for the irrigated Airport field or the studied wild blueberry fields of Maine as a whole. When considering the impact of monthly water conditions (different temporal SPEI in Table S2) during the growing season, the correlation between the SPEI and yield was significant for the non-irrigated Baxter field, whereas it was not significant for the irrigated Airport field.

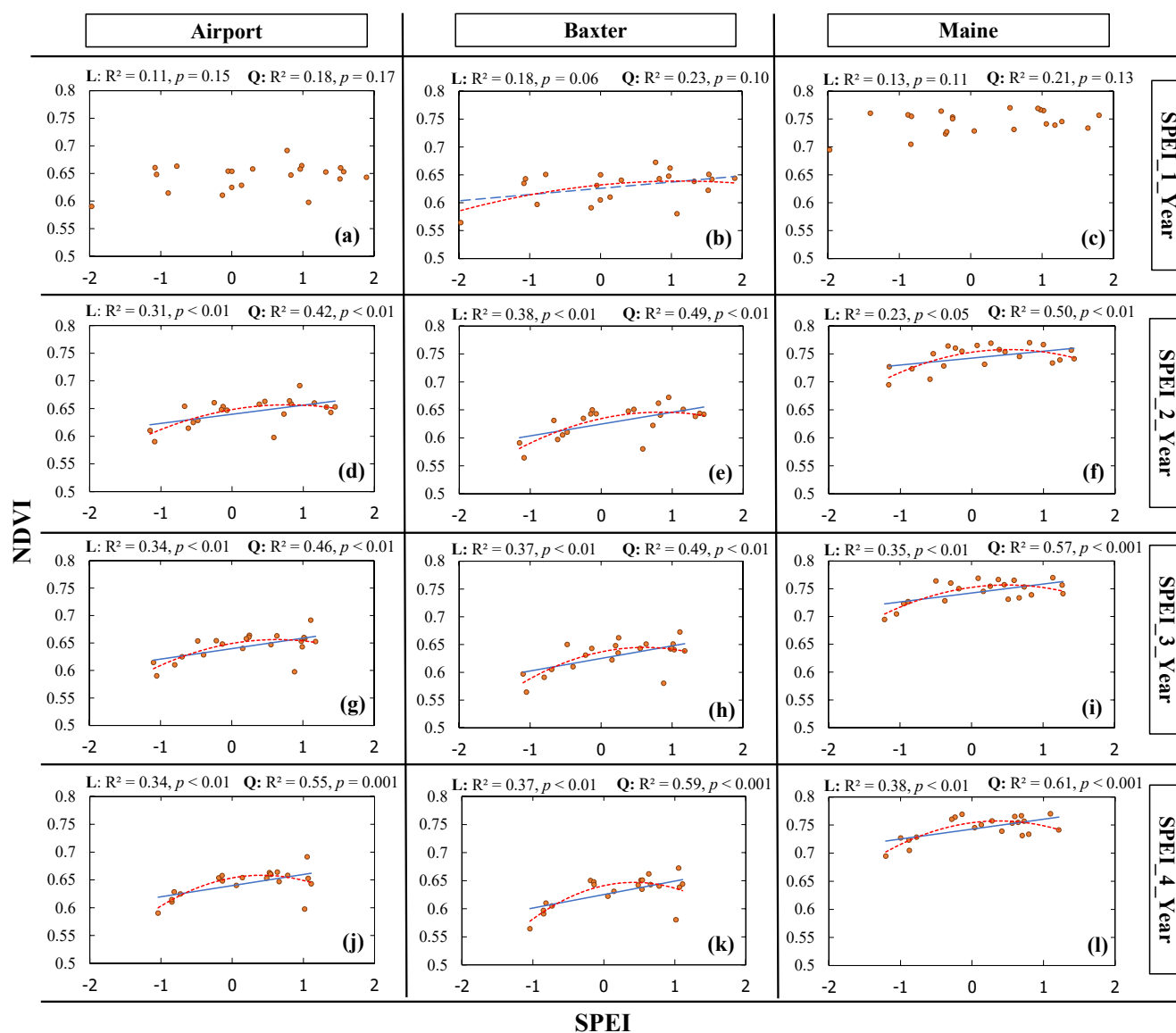


Figure 7. Average normalized difference vegetation index (NDVI) of wild blueberry fields during the growing season (May to September) for three different study zones: Airport (irrigated), Baxter (non-irrigated), and the major wild blueberry production region in Maine in relation to (a–c) SPEI_1_Year; (d–f) SPEI_2_Years (average SPEI of two consecutive years); (g–i) SPEI_3_Years (average SPEI of three consecutive years); (j–l) SPEI_4_Years (average SPEI of four consecutive years). Here, SPEI refers to SPEI_6 of September and it represents the SPEI (water conditions) of the growing season (April–September). A positive SPEI value represents wet conditions, whereas a negative SPEI value indicates dry conditions. The blue solid lines indicate significant ($p < 0.05$) and blue dashed lines indicate marginally significant ($p < 0.10$) linear relationships. The dashed red lines indicate significant ($p < 0.05$) or marginally significant ($p < 0.10$) quadratic relationships. The time period of the EVI and SPEI data was from 2000 to 2020.

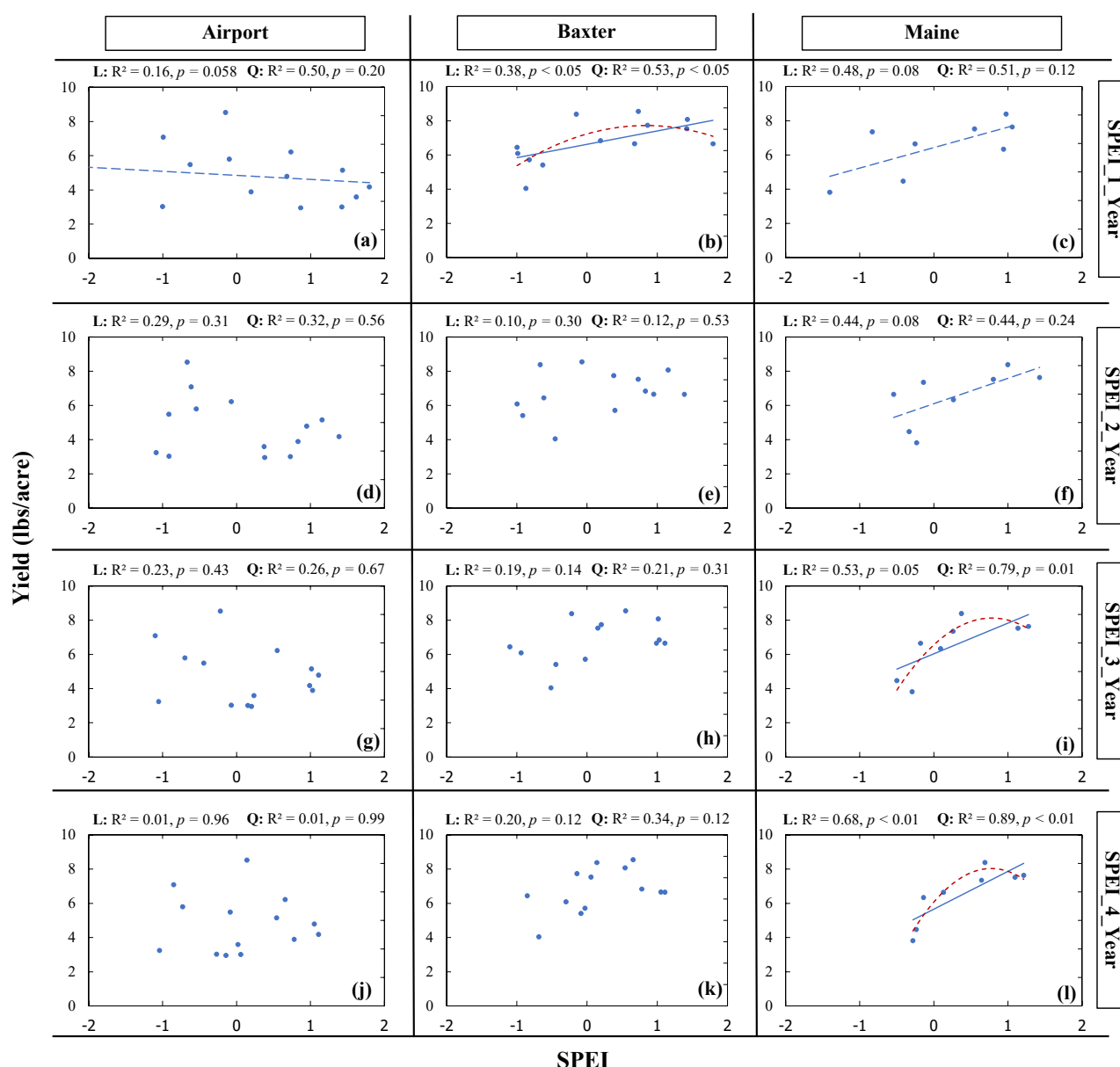


Figure 8. Average yield (lbs./acre) in a year for three different study zones: Airport, Baxter, and the major wild blueberry production region in Maine in relation to (a–c) SPEI_1_Year; (d–f) SPEI_2_Years (average SPEI of two consecutive years); (g–i) SPEI_3_Years (average SPEI of three consecutive years); (j–l) SPEI_4_Years (average of SPEI of four consecutive years). The SPEI data represent SPEI_6 of September. Here, SPEI refers to SPEI_6 of September and it represents the SPEI (water conditions) of the growing season (April–September). A positive SPEI value represents wet conditions, while a negative SPEI value indicates dry conditions. The numbers mentioned in the Y-axis were shortened by dividing the yield (lbs./acre) by 1000. The blue solid lines indicate significant ($p < 0.05$) and blue dashed lines indicate marginally significant ($p < 0.10$) linear relationships. The dashed red lines indicate significant ($p < 0.05$) or marginally significant ($p < 0.10$) quadratic relationships. The time period of the EVI and SPEI data was from 2000 to 2020.

While analyzing the impact of the long-term SPEI (2 to 4 consecutive years) on the yield of the irrigated Airport field and the non-irrigated Baxter field, no significant linear or quadratic relationships were found (SPEI_2_Year in Figure 8d,e; SPEI_3_Year in Figure 8g,h; SPEI_4_Year in Figure 8j,k). However, stronger relationships were observed between the long-term SPEI during the growing season and yield when considering the wild blueberry fields of Maine as a whole (Figure 8i–l). We found significant positive linear and quadratic relationships between the average yield of the wild blueberry fields in Maine and the long-term SPEI (Figure 8i–l), except for the SPEI_2_Year (Figure 8f), where the linear relationship

was marginally significant ($R^2 = 0.36$, $p = 0.08$) and the quadratic relationship was not significant. In fact, the quadratic relationships were stronger between yield and the average SPEI of 3 and 4 consecutive years (Figure 8i–l). Moreover, while considering the cumulative impacts for more consecutive years, both the linear and quadratic relationships were observed to be stronger for the wild blueberry fields in Maine as a whole (Figure 8f,i,l).

3.4. Relationships between Vegetation Indices and Productivity

While comparing the influences of the vegetation indices (EVI and NDVI) on the yield of the irrigated Airport field and the non-irrigated Baxter field, no significant relationship was found between the yield and growing season EVI and NDVI for the Airport and Baxter wild blueberry fields during the prune and crop year (Figures 9 and 10). The only significant correlation was found between the mean EVI of the prune year and crop year for the Airport field and its yield when fitted with the quadratic relationship ($R^2 = 0.65$, $p = 0.03$), whereas the correlation between the mean NDVI of the prune year and crop year for the Airport field and its yield was non-significant.

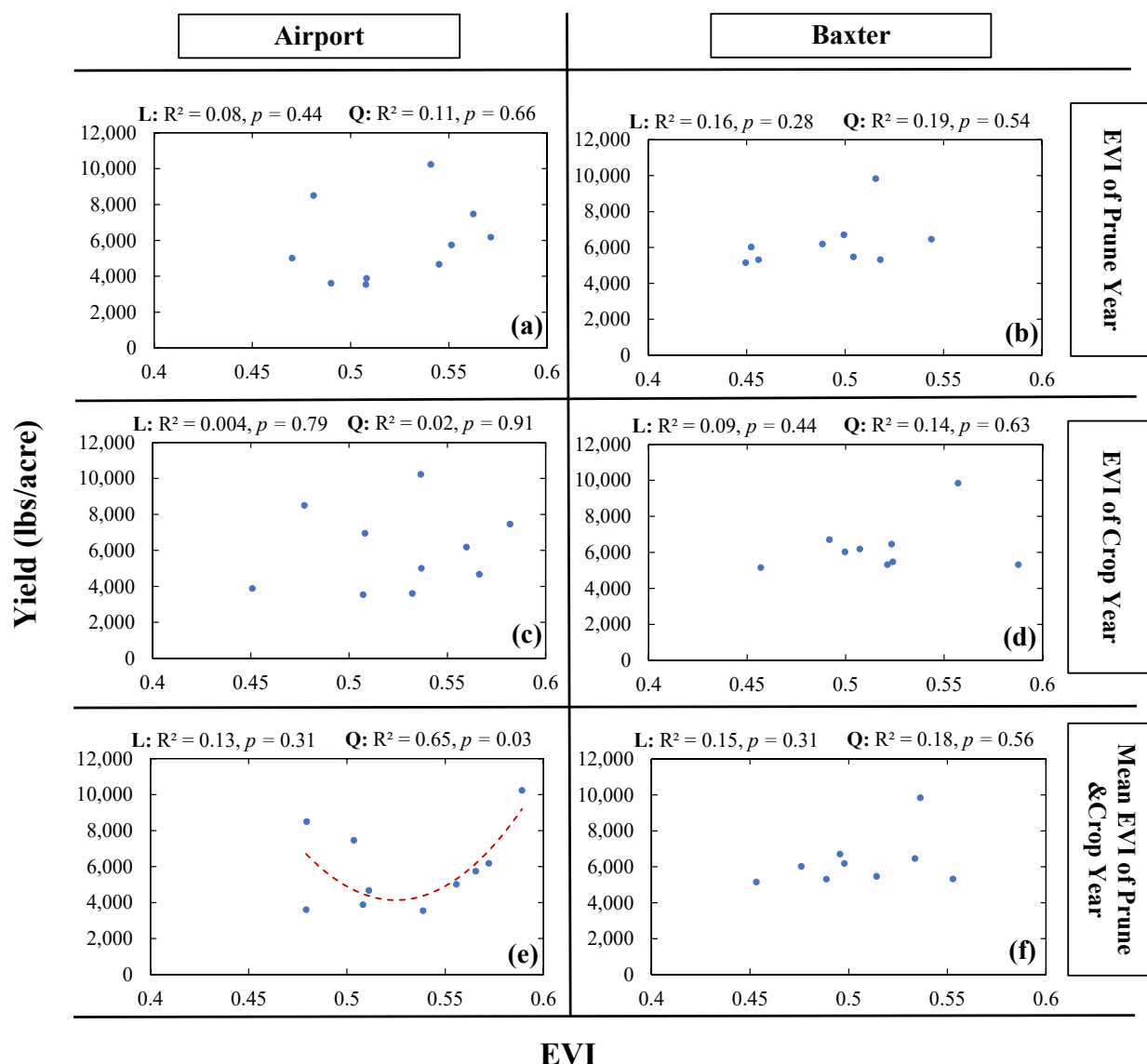


Figure 9. Relationship between wild blueberry yield (lbs./acre) and the average enhanced vegetation index (EVI) of (a,b) the prune year, (c,d) the crop year, and (e,f) the average of the prune and crop year from the Airport (irrigated) and Baxter (non-irrigated) fields in Deblois, Maine. The dashed red lines indicate significant ($p < 0.05$) or marginally significant ($p < 0.10$) quadratic relationships.

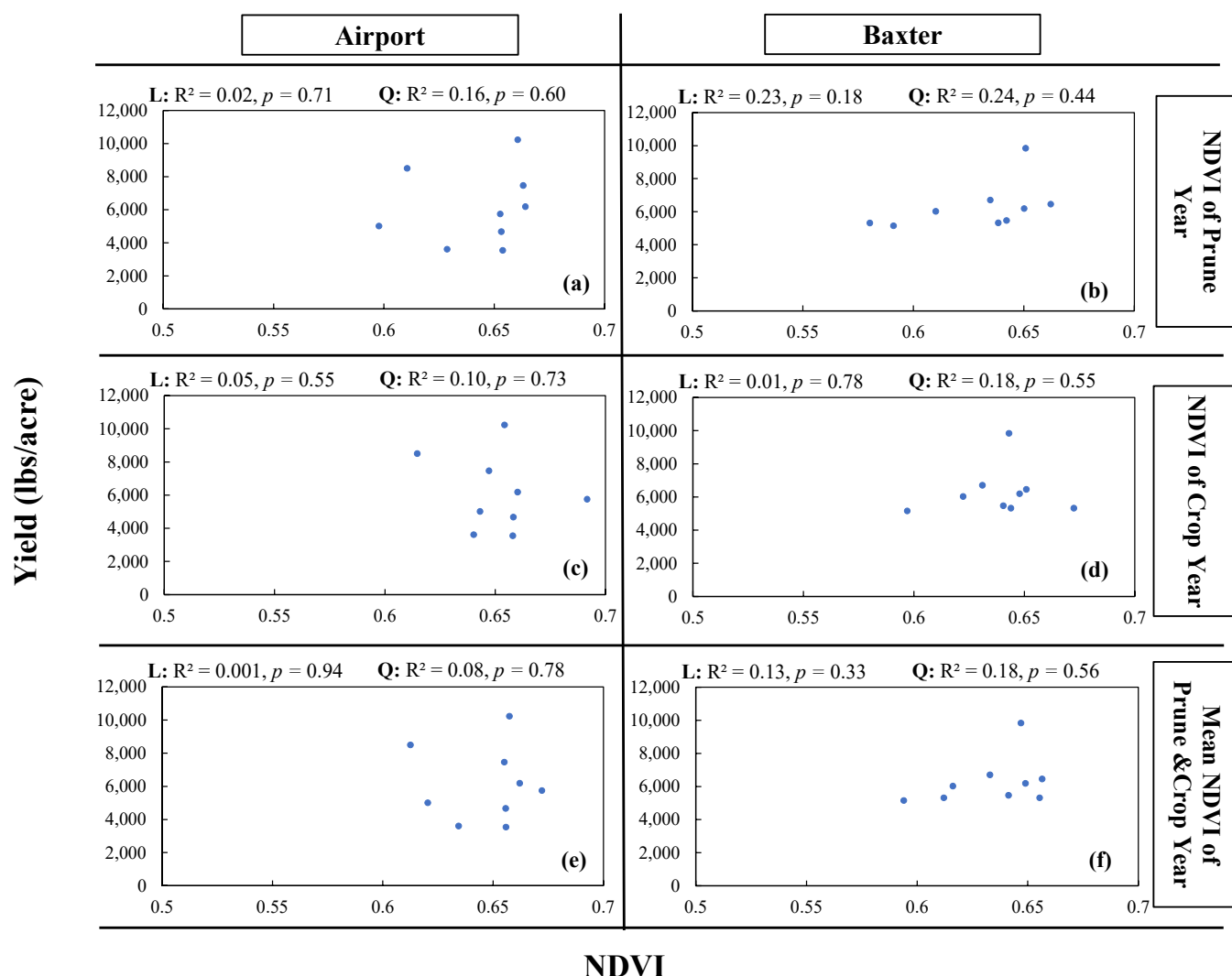


Figure 10. Relationship between wild blueberry yield (lbs./acre) and the average normalized difference vegetation index (NDVI) of (a,b) the prune year, (c,d) the crop year, and (e,f) the average of the prune and crop year from the Airport (irrigated) and Baxter (non-irrigated) fields in Deblois, Maine.

4. Discussion

Our study revealed that, despite significant warming in the past century, there were no significant changes in the drought patterns and drought impacts on the wild blueberry fields of Maine in the past 71 years. We also found that the water conditions (dry or wet, as indicated by the SPEI) in the growing season have significant impacts on wild blueberry vegetation vigor (as indicated by the NDVI and EVI) and production. The long-term water conditions (the long-term average SPEI) have substantial significant impacts on wild blueberry crop vegetation vigor (vegetation indices: NDVI and EVI) as well as their production (yield) in Maine, rather than the water conditions (SPEI) of the current growing season. The impact of the water conditions on the vegetation indices was more consistent and significant compared to the impact on yield. Interestingly, we also found that the water conditions of the early growing season (April–June) might decide the fate of crop vegetation vigor and production of wild blueberry later in the season (July–August). We further found that, in terms of vegetation status, water conditions had little impact on the irrigated field. The water conditions indicated by the SPEI had no impact on the yield of the irrigated field, suggesting irrigation effectively alleviated the impact of water deficits on the yield of wild blueberries. Based on our analyses, we also

found that satellite-based vegetation indices (NDVI and EVI) cannot be used to predict wild blueberry crop production. However, several previous studies found significant correlations between high-resolution spectroradiometer-based vegetation indices and yield in different crops, i.e., maize, wheat, and soybean [32–34]. This could be because the yield of the wild blueberry crop is more affected by other factors such as pollination rather than the vegetation vigor. Moreover, further research could be carried out to test using drone-based high-resolution data to predict the yield of wild blueberries.

The absence of an increasing trend of the drought index SPEI in the wild blueberry fields could be associated with a lack of significant change in precipitation patterns during the growing season [6,15,35]. Although the atmospheric temperatures increased significantly in this region and in the wild blueberry fields in the past century [4–6,10,11], the warming pattern and subsequently increased evapotranspiration [6] have not resulted in a significant increase in drought impact. The studied fields are in a temperate climate region and they experience relatively low temperatures. The increase in evapotranspiration due to warming in this region has possibly not pushed the ecosystems here into the range of severe water deficits.

The water conditions of a relatively long period (SPEI of more than 11–12 months) showed significant and substantial impacts on vegetation vigor and the yield of wild blueberry crops. This could be because wild blueberries are a crop with large perennial underground stem systems called rhizomes, which can store sugar and nutrients [12–14,25], and their health and yield could mostly be determined by the sugar accumulation of previous years and not only that of the current growing season. Although the aboveground parts of the wild blueberries are pruned to the ground every two years, the belowground rhizomes and roots remain for a long time. As a result, the sugar stored underground could govern the effect of precipitation on the crop over the long term [36,37]. The wild blueberry crop requires only an inch of water per week [38] and is regarded as a drought-resistant crop [13,14]. This could be because of the large water and sugar storage in their underground tissues. The underground storage may weaken the effect of current year water conditions on crop health and yield.

The water conditions certainly affect the vegetation status and vigor of wild blueberries. The vegetation greenness or vigor of wild blueberries during both prune and crop years is affected by atmospheric temperature and precipitation during the growing period [6]. Also, precipitation directly affect the soil moisture availability to crops [39]. Furthermore, soil moisture availability affect the nitrogen uptake and accumulation in plants, which consequently determines leaf photosynthetic capacity [40], growth and yield of crops. However, a previous study on the wild blueberries in Eastern Canada found no correlations between the climate variables of that region and wild blueberry yield [41]. Further studies and analyses are needed to establish high-resolution relationships among climate variables, vegetation vigor, and yield.

Here, the vegetation indices (EVI and NDVI) are not good predictors of the yield of wild blueberries. This could be because, besides vegetation status, wild blueberry yield during the crop year is affected by many other important factors [42], such as pollination, insect pests, weeds, and pathogens. Though it has been found that vegetation indices are strongly correlated with yield in some crops [34], it might not be the case for wild blueberries. Vegetation indices are correlated with leaf chlorophyll content and photosynthesis capacity [43], and might be related to the number of developed flower buds [44]. However, there are a lot of other factors such as pollinator activity, weed coverage, and fruit set ratio, which are important in determining yield but can not be predicted by vegetation indices.

Water conditions (indicated by the SPEI) during the early growing season (April–June) have a larger impact on the vegetation status and yield of wild blueberry crops compared to that of the later growing season (July–September). This could be related to pollination. Precipitation intensity and frequencies, along with temperature and wind velocity, during the pollination period (April–May) in crop year would affect the bee pollination, which significantly affects the wild blueberry yield in July and August [42,45–47]. In addition,

the availability of resources such as soil moisture and nutrients [42], determined by the precipitation and temperature [38], during fruit set and maturation (May–June) right after the pollination period ends, decides the fate of the final fruit production (July–August) [45–48].

Irrigation decoupled the relationship between the climatic water condition (SPEI) and yield. The positive relationship between SPEI and yield found in the non-irrigated Baxter field was not found in the irrigated Airport field, despite both fields being in the same location with same management practices (except irrigation). The positive correlation between the SPEI and the yield of the non-irrigated Baxter field suggests the importance of water conditions in determining yield and the need for effective irrigation practices to alleviate the impact of drought. The fields of the major wild blueberry region (which are mostly non-irrigated) showed similar patterns to the non-irrigated Baxter field. Thus, it suggests that the introduction of effective irrigation management practices might be useful to enhance the production of wild blueberries by mitigating drought. Additionally, wild blueberries respond more positively to precipitation frequency rather than total precipitation volume over the growing season [49]. Irrigation also decoupled the relationship between the SPEI and vegetation indices (EVI and NDVI), suggesting the positive effect of irrigation in mitigating the drought effects on vegetation vigor for wild blueberries. Meanwhile, the quadratic relationships between the SPEI and vegetation indices, as well as the SPEI and yield, suggest that when the optimum precipitation or water supply is reached, further increases in the water supply may have a negative effect on crop vigor and yield. Similar results were also reported between the EVI and precipitation from the wild blueberry fields in Downeast, Maine [6]. Hence, no overall significant differences in the vegetation indices or yield were observed between the irrigated Airport field and the non-irrigated Baxter field, but in drought years (e.g., 2003), the yield and EVI of the irrigated field were higher than that of the non-irrigated field.

5. Conclusions

Overall, our study suggests that though the temperature has been increasing significantly in the major wild blueberry production region of Maine, drought has not been increasing significantly over the last 71 years. However, accelerated warming and a projected decrease in soil water content [7] may result in an increase in drought impact on agricultural systems in the future [48]. The water conditions and drought severity quantified by the drought index SPEI had a stronger impact on the vegetation status of the non-irrigated field compared to the irrigated field. The short-term (one year) SPEI was positively related to the yield of the non-irrigated field, whereas no significant correlation was found for the irrigated field, suggesting the sensitivity of wild blueberry yield to water conditions and the effectiveness of irrigation. However, maintaining optimum soil moisture is a challenge due to the high spatial variability in soil water retention capacity in wild blueberry fields. Therefore, developing a precision irrigation system could be an efficient way to mitigate the effects of water deficits. Interestingly, we found that long-term water conditions determine the vegetation vigor and yield more than the short-term water conditions for wild blueberries. Thus, although the wild blueberry is regarded as a drought-tolerant species, maintaining good water conditions in the field during the growing season is important for securing a high yield for wild blueberries.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/cli9120178/s1>: Table S1. Pearson correlation analysis between average enhanced vegetation index (EVI) of the growing season (May–September) and different scales of the SPEI from May to September at three different wild blueberry study zones: Airport (irrigated field, Deblois, ME), Baxter (non-irrigated field, Deblois, ME), and Downeast, Maine (all wild blueberry fields). Table S2. Pearson correlation analysis between average yield per year and different scales of the SPEI from May to September at three different wild blueberry study zones: Airport (irrigated field, Deblois, ME), Baxter (non-irrigated field, Deblois, ME), and Maine (all wild blueberry fields).

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Data Availability Statement: Please refer to “Section 2.2” in this article for the sources of the publicly archived data products used in this study. Any data and codes used in this study are available upon request from the corresponding author (yongjiang.zhang@maine.edu).

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Conflicts of Interest: The authors declare no conflict of interest.

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