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Relations between NDVI and tree productivity in the central Great Plains

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Abstract. Remotely sensed Normalized Difference Vegetation Index (NDVI) is a good measure of photosynthetic activity at landscape scales, and can be used to estimate productivity. Our research demonstrates strong relations between NDVI and ground-based measurements of productivity for forest trees in the central Great Plains. Standardized tree ring width, diameter increase and seed production all are strongly correlated with integrated NDVI of the same growing season. Tree height growth for a given year corresponds with integrated NDVI of the previous year, i.e. a one-year lag. Variation in foliage production, as measured by litterfall, generally corresponds with variation in NDVI, but not as distinctly as do other tree productivity measures. Although foliage production is best correlated with NDVI integrated over the entire growing season, most tree productivity measurements are best correlated with NDVI integrated over the early growing season. All tree productivity measures, except foliage production, are better related to NDVI averaged over an intermediate spatial scale (7×7 pixels, $\sim 50\,km^2$), rather than just local NDVI (1 pixel, $1.2\,km^2$). Overall, NDVI is an excellent predictor of annual tree productivity.

1. Introduction

Woody plant productivity is typically measured at local scales, whereas satellite remote sensing provides a synoptic view at a broader landscape scale. Detailed studies are needed to understand linkages between these local and landscape scales. Normalized Difference Vegetation Index (NDVI), calculated as the difference between near-infrared and visible reflectance values normalized over the sum of the two (Eidenshink and Faundeen 1994), has been proposed as a means to estimate

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landscape patterns of productivity. NDVI is strongly related to photosynthetic activity because the internal mesophyll structure of healthy green leaves strongly reflects near-infrared radiation, while leaf chlorophyll and other pigments absorb a large proportion of the red visible radiation (Gausman 1974, Sellers 1985, 1987, Tucker and Sellers 1986, Sellers *et al.* 1992). Remotely sensed NDVI has been widely used to estimate landscape patterns of primary production and biomass (Gausman 1974, Rosental *et al.* 1985, Sellers 1985, 1987, Tucker and Sellers 1986, Goward and Dye 1987, Prince 1991, Sellers *et al.* 1992, Hayes and Decker 1996, Paruelo *et al.* 1997, Tieszen *et al.* 1997, Wang *et al.* 2001, 2003). Estimates of annual production and net carbon dioxide flux are generally assumed to relate directly to NDVI integrated over the growing season.

Most previous studies have focused on herbaceous plants, either on grasslands or croplands, but only a few studies have explored the linkages between NDVI and tree growth (e.g. Bonan 1993, Franklin *et al.* 1997). Goetz and Prince (1996) calculated photosynthetically active radiation interception (IPAR) using NDVI and found a strong relationship between IPAR and measured annual aboveground net primary production in young stands of quaking aspen (*Populus tremuloides*) and black spruce (*Picea mariana*) in the boreal forest of northeast Minnesota. Malstrom *et al.* (1997) found a strong correlation between tree-ring data and NDVI-based net primary productivity estimates. Coops *et al.* (1999) also found that there was a stronger relationship between NDVI and canopy area index with the 3×3 averaged pixel response rather than the single pixel response. D'Arrigo *et al.* (2000) found that in boreal conifers, maximum latewood density of annual rings was significantly correlated with NDVI. This study examines relations between NDVI and three types of field measurements of production: tree ring analysis, stem growth (diameter and height), and litterfall (foliage and seeds). Each of these measurements relates to annual aboveground production. A tree ring is literally new woody stem tissue generated during a particular year, and relative tree ring size relates well to overall annual tree growth (Fritts 1976). Similarly, stem diameter and height increment are widely used to characterize annual tree growth, and litterfall is an excellent measure of annual forest production (Newbould 1967, Madgwick and Satoo 1975). Rather than assuming that the entire growing season is the appropriate temporal scale for integration, we examine a full spectrum of timescales to determine which time interval generates the strongest correlation between NDVI and the various production measurements.

2. Methods

2.1. *Study area*

This study was conducted in eastern Kansas, located in the central Great Plains region of North America. Annual precipitation of Kansas ranges from less than 450 mm in the west to more than 1200 mm in the southeast (Wang *et al.* 2001). Annual mean temperature ranges from 15°C in the southeast to 10.5°C in the northwest. The natural vegetation in Kansas ranges from shortgrass prairie in the west to a mosaic of tallgrass prairie and oak-hickory forest in the east (Kuchler 1974, Abrams 1986, Loehle *et al.* 1996).

Ground data concerning tree productivity were collected from three sites within Kansas (figure 1):

(1) Fort Leavenworth Military Reservation (FLMR), a densely forested area located along the west side of Missouri River valley, 5 km north of Leavenworth. The study site is within a stand of about 400 ha of undisturbed

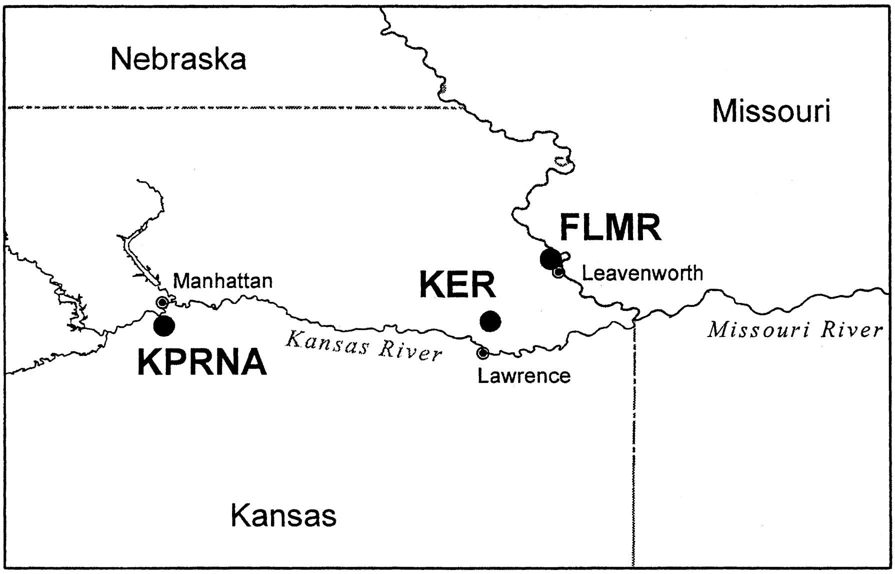

Figure 1. Locations of the three study sites in eastern Kansas: Fort Leavenworth Military Reservation (FLMR), Kansas Ecological Reserves (KER), and Konza Prairie Research Natural Area (KPRNA).

old-growth forest on steep slopes of well-drained soils. Detailed tree ring measurements were obtained for studies of trees with maximum ages of 150 to 200 years (Noam 1998).

(2) Kansas Ecological Reserves (KER), an area of planted trees, located 12 km north of Lawrence, KS (Fitch and Kettle 1988). The study site is a 1.7 ha plantation, consisting of 1100 white ash trees (*Fraxinus americana* L.), planted in 1976 on a ridge with gentle slopes and well-drained soils (Clausen 1984). Annual height and stem diameter growth measurements were obtained for each tree in the plantation.

(3) Konza Prairie Research Natural Area (KPRNA), a 3000 ha natural area located in the Flint Hills region, about 10 km south of Manhattan (Knight *et al.* 1994). The gallery forest has been expanding in this area since the mid-1800s (Knight *et al.* 1994). Annual litterfall measurements were obtained from a 21-ha gallery forest (about 3.5 km long by 100–200 m wide) on moderately well-drained soils (Ransom *et al.* 1998) along the valley of the north branch of Kings Creek, which flows into the Kansas River.

2.2. *Data collection and processing*

Tree ring data: Noam (1998) obtained tree ring cores from oak trees (*Quercus* spp.) located at FLMR ($n=29$). Ring width was measured for the period from 1967–1996, cross-dated, and standardized to remove age-related trends, yielding standardized width residual values. The current study analysed standardized tree ring values for an 8-year period (1989–1996).

Tree growth: From 1976–1994, height was recorded annually after the autumn leaf fall and before the onset of spring growth at KER. For trees with multiple stems, the tallest stem was measured each year. Starting in 1989, diameter at breast height (DBH, 1.3 m height) was measured to the nearest 0.25 cm for all trees with

DBH greater than or equal to 7.0 cm. The current study analysed stem diameter and height growth for a 5-year period (1989–1993). For diameter growth, separate analyses were performed for single-stem trees ($n=14$) and multiple-stem trees ($n=48$) that were measured at all years. For height growth, analyses included five height classes: 3–4 m ($n=121$), 4–5 m ($n=123$), 5–6 m ($n=123$), 6–7 m ($n=122$), >7 m ($n=60$).

Litterfall: In 1981, thirty 50 cm × 50 cm litterfall traps were placed according to a stratified random design in the gallery forest along the north fork of Kings Creek in KPRNA. Collections were made periodically through each year, with most intensive collection in the fall. Plant materials were sorted into categories (seeds, foliage, woody debris), dried at 60°C, and weighed (Killingbeck 1986). The current study analysed seed and foliage production for a nine-year period (1989–1997).

NDVI: Both biweekly and growing season NDVI values for the study sites were derived using National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer (NOAA/AVHRR) satellite imagery. This imagery consists of 1.1 km resolution Maximum Value Composite NDVI compiled by the United States Geological Survey EROS Data Center, Sioux Falls, SD. The imagery was further processed to remove cloud contamination and made available by the Kansas Applied Remote Sensing Program at the University of Kansas, Lawrence, KS.

2.3. *Correlation analysis between NDVI and tree production*

Minimum, maximum, and mean NDVI values for the three study sites were calculated from the biweekly images for a series of different window sizes surrounding each study site. Window size ranged from 7 pixels × 7 pixels (59.3 km^2) to 11 pixels × 11 pixels (146.4 km^2) for the tree ring study site (FLMR), with 7 pixels × 7 pixels as the minimum window size that included all trees sampled. Window size ranged from one pixel (1.2 km^2) to 11 pixels × 11 pixels (146.4 km^2) for the tree growth (KER) and litterfall sites (KPRNA). These NDVI values were calculated for all possible combinations of time interval (1–21 biweekly periods) and starting time (March to October). Correlation coefficients were then calculated between NDVI and each of the production indices as a function of window size, time interval, and starting time. Data from 1993 were excluded from the calculation of correlation coefficients at FLMR because of flood conditions in eastern Kansas (Wang *et al.* 2003).

3. Results

3.1. *Relations between tree rings and NDVI*

The correlation coefficients between standardized tree ring width residuals and NDVI show different patterns for average, maximum, and minimum NDVI values, as well as for different window sizes; and for different time intervals over which NDVI values were integrated.

For NDVI integrated from late April, when buds opened, to October, when leaves fall, the best correlation coefficients are between tree ring width residuals and average NDVI at the window size of 9 pixels × 9 pixels (table 1). Tree ring width residuals and NDVI generally covary (figure 2), except during 1993, which was a flood year. In addition, tree ring width residuals also are strongly correlated with average NDVI integrated from mid-May to late June, and the correlation coefficients are 0.91, 0.91 and 0.87, respectively, for the window sizes of 7 × 7, 9 × 9, and 11 × 11 pixels.

Table 1. Correlation coefficients between tree ring width residuals and average, maximum, and minimum NDVI values integrated from late April to October at window sizes of 7×7, 9×9, and 11×11 pixels.

Window size	Average NDVI	Maximum NDVI	Minimum NDVI
7×7	0.76	0.25	0.58
9×9	0.86	0.35	0.56
11×11	0.54	0.34	0.59

3.2. *Relations between growth and NDVI*

In general, diameter growth is correlated with NDVI at KER. Diameter growth shows very strong correlation with NDVI integrated from March to early May, mid-June to early July, and also for the whole growing season (March to early October) (table 2, figure 3). The correlations are strongest for average NDVI using larger window sizes. For trees with multiple stems, diameter growth only shows strong correlation with average NDVI when NDVI is integrated over a longer time interval (late May to early July) than for single-stem trees. Diameter growth of single-stem trees closely followed NDVI in all years (figure 3), whereas diameter growth of multiple-stem trees followed NDVI in all years except 1992 (data not shown).

For trees at KER, height increase does not correlate with NDVI in the current year, but variation in height increase is related to variation in NDVI of the previous year, i.e. a 1-year time lag exists (figure 4). Since height data are only available for 5

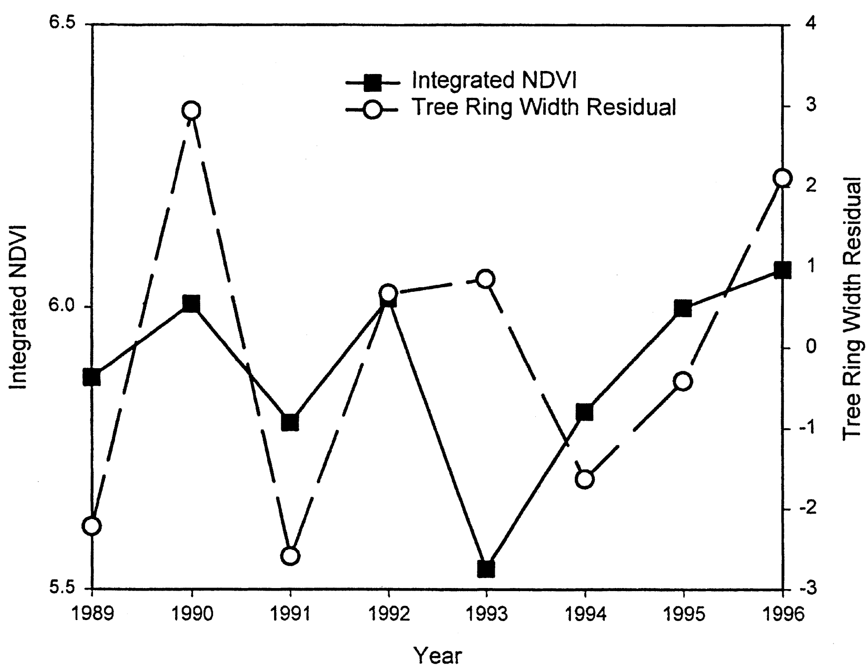

Figure 2. Annual tree ring width residuals and average NDVI (integrated from late April to October, using a 9 pixel × 9 pixel window) at Fort Leavenworth Military Reservation.

Table 2. Correlation coefficients (r-value) between tree diameter increases and average NDVI integrated over different time intervals and using different window sizes.

	Single stem		Multiple stem	
Window size (pixels)	1 March – 23 May	7 June – 4 July	1 March – 10 October	24 May – 4 July
1 × 1	0.841	0.48	0.63	0.904
3 × 3	0.970	0.70	0.95	0.995
5 × 5	0.997	0.83	0.83	0.980
7 × 7	0.996	0.86	0.80	0.966
9 × 9	0.999	0.88	0.79	0.921
11 × 11	0.999	0.90	0.79	0.885

years (1989–1993), it is not possible to calculate meaningful correlation coefficients. Taller trees have greater height increments than shorter trees. These differences are relatively small in low growth years and more pronounced in high growth years.

3.3. *Relations between forest litterfall and NDVI*

Seed production is strongly correlated with NDVI integrated from March to late October. The maximum correlation coefficients are 0.76 and 0.79 for average and maximum NDVI using a 3 pixel × 3 pixel window, respectively, and the correlation coefficient is 0.89 for minimum NDVI over a 7 pixel × 7 pixel window.

The correlation is even stronger between seed production and integrated NDVI

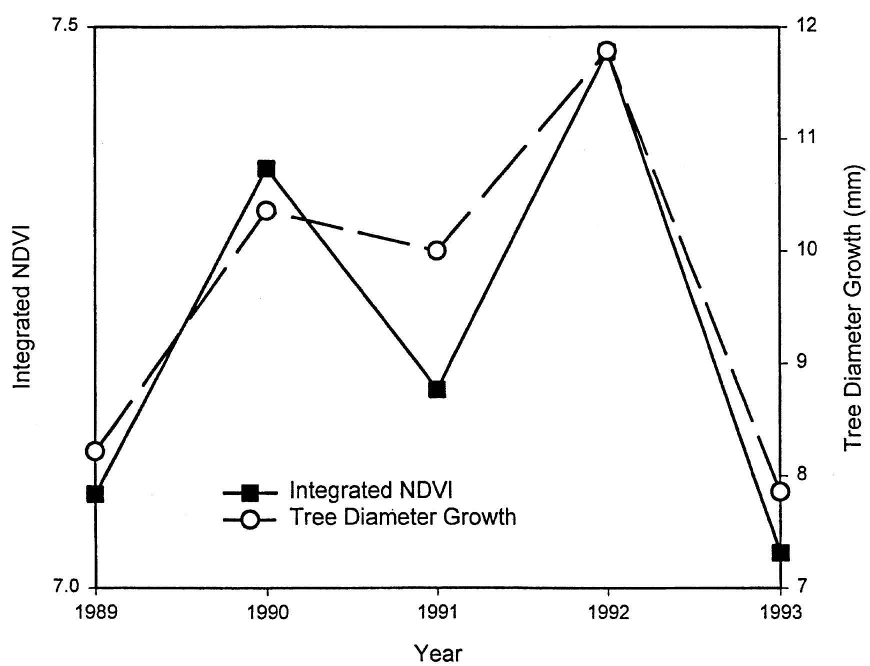

Figure 3. Annual single-stem tree diameter growth and average NDVI (integrated from March to October, using a 3 pixel × 3 pixel window) at Kansas Ecological Reserves.

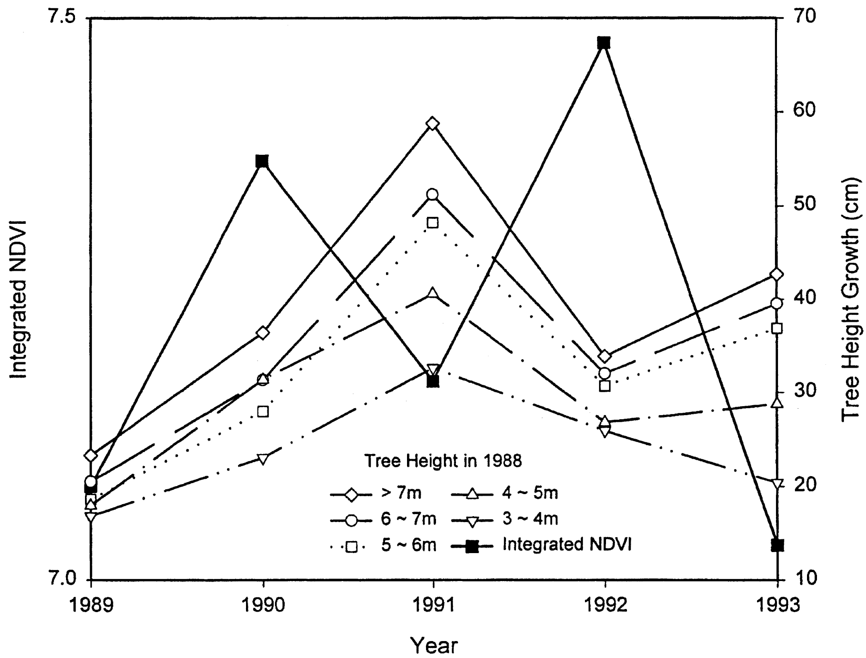

Figure 4. Annual tree height increase and average NDVI (integrated from March to October, using a 3 pixel × 3 pixel window) at Kansas Ecological Reserves.

from late March to late May (figure 5), with the highest correlation for a 7 pixel × 7 pixel window. Correlation coefficients between seed production and minimum NDVI show a similar pattern, but with slightly lower values; whereas correlations between seed production and maximum NDVI sharply decrease as window size increases. Seed production for 1989–1997 covaries with average NDVI integrated from late March to late May, with nearly perfect correspondence (figure 6).

Foliage biomass is best correlated with NDVI integrated from March to October ($r = 0.83$). While foliage and NDVI generally covary between 1989 and 1997, the year-to-year correspondence is weaker than for seed production (figure 7).

4. Discussion

Our analysis shows strong correlation between integrated NDVI and tree production, as represented by tree ring width residuals, diameter increase, and seed and foliage production. By contrast, tree height increase is best related with integrated NDVI of preceding years. Correlations between NDVI and production measures for single biweekly periods are not reliable because of high variation and spurious correlations. Correlations for NDVI integrated over longer periods of time are reliable and meaningful.

Tree ring width residuals for oaks at FLMR covary with NDVI, except during 1993 (figure 3). In 1993, large areas in eastern Kansas were flooded and soils were oversaturated, such that NDVI values for 1993 are much lower than normal (Wang *et al.* 2003). Trees sampled at FLMR were growing on well-drained upland ridges

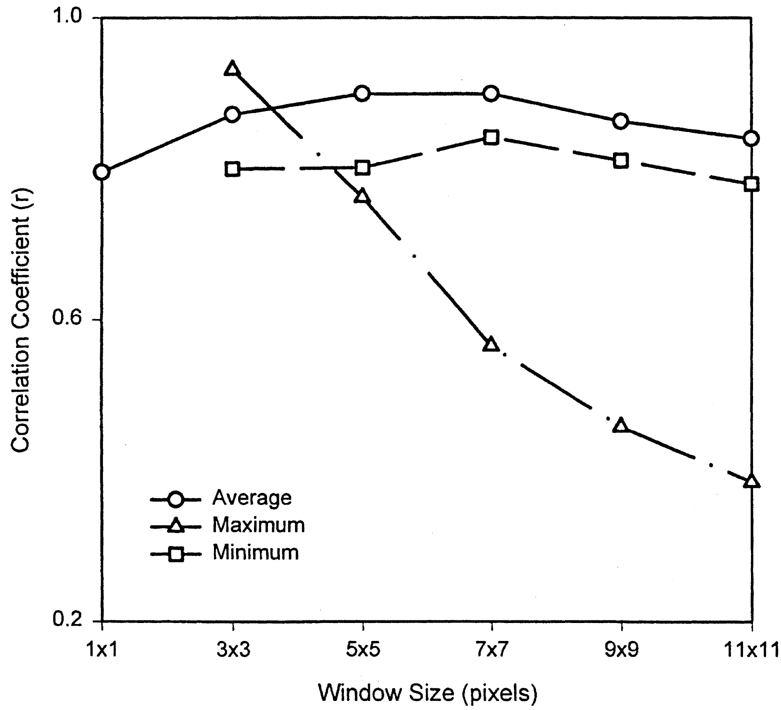

Figure 5. Correlation coefficients between seed production and average, maximum, and minimum NDVI (integrated from mid-March to late May) as a function of window size at Konza Prairie Research Natural Area.

(Noam 1998), such that their growth was likely to be higher than prevailing plant growth in area.

At the KER ash plantation, single-stem tree diameter growth is strongly correlated with integrated NDVI. These trees were planted as seedlings at equal distances and the understory has been mowed periodically such that competition with other woody species is minimal. Under such ideal growing conditions the main cause of differences in growth from year-to-year is precipitation. By contrast, correlations for the multiple-stem trees are not strong. This may be attributed to competition between different stems, and to a sampling artifact that different stems may have been measured in different years (only the largest stem in a given year was measured). In general, there is a one-year lag between changes in NDVI and changes in height growth. Thus, we found that increase in production in a given year leads to increase in height growth in the next year.

For litterfall studies in gallery forest at KPRNA, both seed production and foliage production are strongly correlated with integrated NDVI. Year-to-year variation in annual seed production corresponds fairly well with year-to-year variation in NDVI, while covariance between foliage production and NDVI is somewhat weak. This result for the seed production is surprising, given high year-to-year variance in seed production for individuals of certain tree species, notably oaks (Schopmeyer 1974).

Tree diameter is known to increase more in the early growing season than in the late growing season. The fastest growth rates are in May and June, especially for

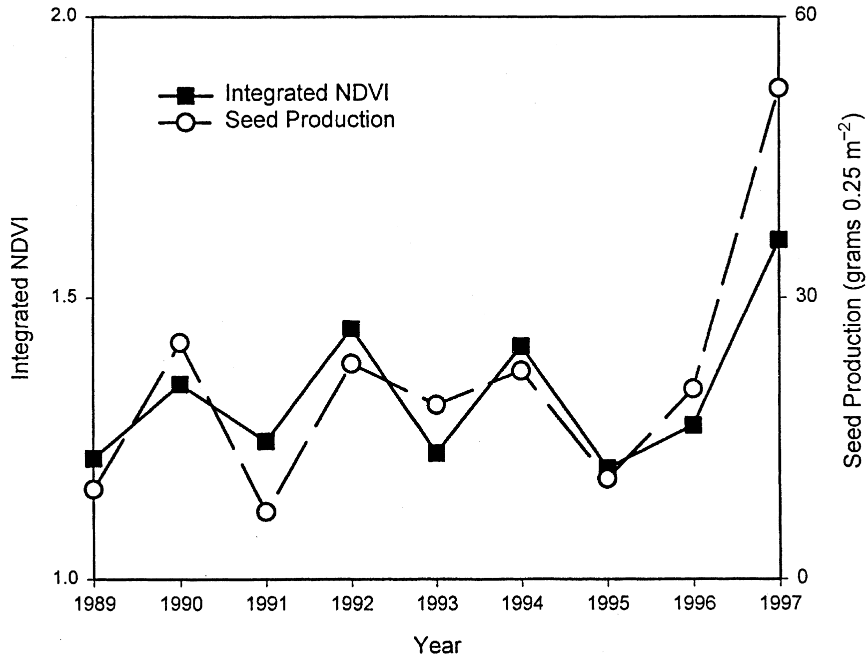

Figure 6. Annual seed production and average NDVI (integrated from mid March to late May, using a 7 pixel × 7 pixel window) at Konza Prairie Research Natural Area.

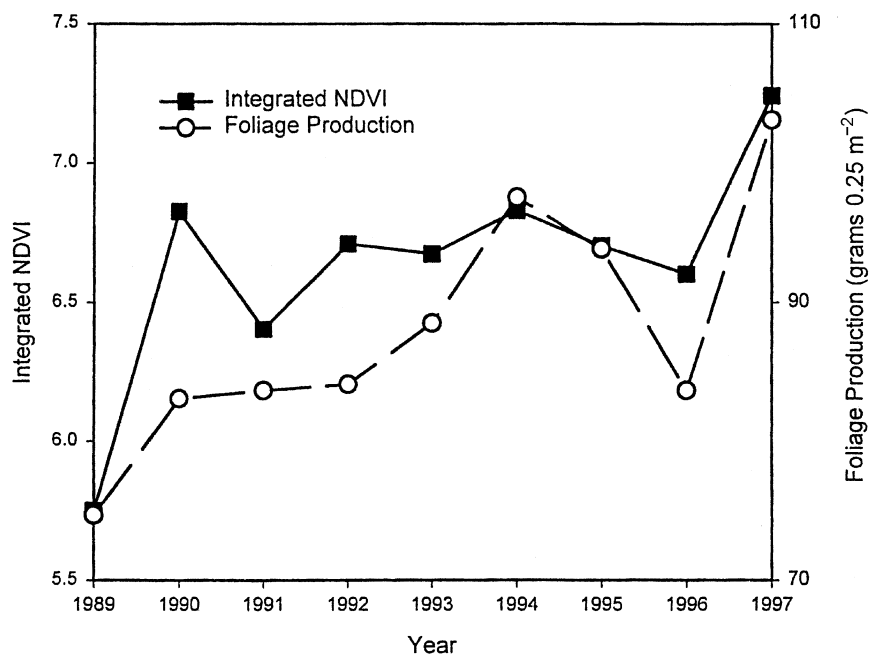

Figure 7. Annual foliage production and average NDVI (integrated from March to October, using a 3 pixel × 3 pixel window) at Konza Prairie Research Natural Area.

trees with ring-porous wood anatomy such as oaks and ashes (Fritts 1976). For example, oaks start diameter growth at the end of April and reach their peak rate of diameter growth after leaves reach maturity in early May. At FLMR, we found that tree ring width residuals are correlated with NDVI from mid-May to late June, although not as strong as with NDVI integrated from late April to October. At KER, single-stem tree diameter growth is more strongly correlated with NDVI integrated from March to late May than with NDVI integrated for the whole growing season (March to October). Although they are not well correlated with integrated NDVI of the growing season, diameter increases of multiple-stem trees at KER are strongly correlated with average NDVI integrated from late May to early July. Thus, our results support the generalization that early season production, which can be monitored at a landscape-level with NDVI, is the most important predictor of tree diameter increase.

At KPRNA seed production is also better correlated to NDVI integrated from mid-March to late May than to NDVI integrated for the whole growing season (March to October). In general, forest tree species bloom early in the spring and many produce mature fruits by mid to late spring (Stephens 1969). Among the three dominant species of the gallery forest, American elm (*Ulmus americana*) flowers in March and fruits in early May, bur oak (*Quercus macrocarpa*) flowers in late April, and chinquapin oak (*Q. muehlenbergii*) flowers in early May (Knight *et al.* 1994). Fruits of the later species typically mature by September or October. Insofar as seed production is related to flowering success and early-season resources available for fruit growth, it makes sense that early season production has a strong influence.

Among average, maximum, and minimum NDVI values in various size windows of analysis, average NDVI values have the strongest and most reliable correlations with tree growth (table 1, figure 5); maximum NDVI has variable correlations; and minimum NDVI has moderate to strong correlations. An intermediate window size surrounding each study site (5×5 to 9×9 pixels) has the highest correlations. Corresponding pixels on the NDVI images for different years may not represent identical locations due to georegistration errors, such that temporal change of NDVI may not represent the changes in vegetation conditions of an exact location through different years. By contrast, integrated NDVI over a larger window size represents the prevailing local vegetation condition, greatly reducing artifacts caused by georegistration error, and leading to much stronger correlations. This is in accordance with the study by Coops *et al.* (1999). The surrounding areas of our study sites are typically dominated by cropland or grassland, not by forest. Even so, tree productivity measurements are strongly correlated with NDVI in such large areas because both the forest and the other vegetation grow under similar climate conditions. Thus tree productivity measurements are good indicators of the general conditions for growth in an area.

5. Conclusion

NDVI can be used as a reliable predictor of landscape level patterns of productivity in woody species, especially if appropriate scales for temporal and spatial integration are used. We found very strong correlations between current-year integrated NDVI and tree production, as measured by ring width variation, diameter growth, and seed and foliage production. By contrast, tree height increase is related to changes in NDVI from the previous year (i.e. a 1-year time lag). For tree ring size, stem diameter, height increment, and seed production, early growing season NDVI is the best predictor of annual production. For foliage litterfall, NDVI integrated over the entire growing season is the best predictor. Among average, maximum, and minimum NDVI values and different window sizes, average NDVI values in an intermediate window size (5×5 to 9×9 pixels) showed the best correlation with tree production measures. The strong correlations between tree productivity measurements and NDVI, integrated over areas that are not dominated by forests, supports the assumption that tree productivity can be used as an indicator of local climate conditions that affect growth in general.

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