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# Cropland Area and Net Primary Production Computed from 30 Years of USDA Agricultural Harvest Data

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Received 15 October 2003; accepted 1 January 2004

**ABSTRACT:** Croplands cover large areas of the globe and contribute significantly to the global carbon cycle. However, like other ecosystems, limited information exists on spatially explicit, ground-based estimates of carbon fluxes. In this study, county-level cropland area and harvest information reported in the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) from 1972 to 2001 was utilized to calculate the temporal behavior of net primary production (NPP) for croplands across the United States. Production data for individual crops were converted to estimates of NPP using crop-specific factors. Because NASS does not include all crops of interest during all years, only a crop type in a county estimate was included if the entire time series was complete. Incomplete reporting occurred primarily with hay. Trends in crop area, NPP, and total production (area times NPP) exhibited significant spatial variation. The largest increases in production occurred in the Midwest, Great Plains, and Mississippi River Valley regions.

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Cropland area exhibited a range of trends from large percent increases in counties across the Great Plains and the West to decreases across the South. Generally, NPP increased in counties throughout the United States and for the country as a whole. It was estimated that total coterminous cropland production increased during 1972–2001 from 0.37 to 0.53 Pg C $yr^{-1}$, a 40% increase over 1972 values. Since total cropland area changed little during the 30-yr period, production increases were driven primarily by gains in NPP.

**KEYWORDS:** Cropland production, Yields, Net primary production, Biogeochemical processes

## 1. Introduction

Croplands are important land-cover types in the global carbon (C) cycle. Worldwide, croplands cover 12% of the total vegetated land surface (Ramankutty and Foley, 1998). Studies of net primary production (NPP), the net amount of carbon fixed by plants, estimated that 7.8 Pg C $yr^{-1}$ is associated with croplands, or 16% of the global total (Potter et al., 1993). In the coterminous United States, croplands contributed an average of 20% of the total NPP from 1982 to 1998 (Hicke et al., 2002b; Lobell et al., 2002).

Changes in agricultural production therefore have the potential to significantly impact the U.S. carbon cycle. Carbon fixed by crops may be transferred to the soil through root production or through residues remaining after harvest. In addition, the harvested mass (e.g., grain) is consumed and respired back to the atmosphere. This harvest may be respired locally, may be transported long distances within the United States before being consumed, or may be exported to other countries or continents before being consumed. In the latter case, depending on destination, this export appears as a C sink in atmospheric inversion model results (Pacala et al., 2001).

A recent study of North American NPP using 17 yr of satellite observations identified the central United States as an area of large NPP increase (Hicke et al., 2002a). Although satellite data provided reasonable estimates of changes in vegetation activity, mechanisms driving these changes were more difficult to determine. Long-term (e.g., decadal) remote sensing analyses of canopy greenness and energy absorption are becoming routine (Goetz et al., 2000; Hicke et al., 2002a; Lobell et al., 2002; Myneni et al., 1997; Tucker et al., 2001), but large-scale, high-resolution data have not been available to evaluate remotely sensed measures. Hicke et al. (Hicke et al., 2002a) proposed that the large increase in NPP during the 1980s and 1990s in the central United States was likely driven by increased agricultural production, but no comprehensive, independent data analyses were available for comparison to the satellite-derived estimates.

Although changes in cropland area have been reported by the U.S. Department of Agriculture's (USDA's) Census of Agriculture (e.g., USDA, 1992), the conversion of production estimate to a more biologically meaningful metric is more challenging. For example, although the USDA reports trends in total "productivity" over the most recent 50 yr, this productivity is an economic index. To analyze how changes in agricultural practices have influenced ecosystems

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processes across crop types, one needs to estimate the contribution of each crop type in terms of biological productivity. Here, we have computed NPP (in units of g C $m^{-2}$ $yr^{-1}$). Our study is unique in that we present NPP results for cropland throughout the United States and report the temporal dynamics over 30 yr.

Several recent studies utilized data from the USDA National Agricultural Statistics Service (NASS) (USDA, 2001) to investigate cropland production. Prince et al. (Prince et al., 2001) computed NPP for counties in several Midwestern states in 1992. In Iowa, NPP was estimated for the time period 1982–96. Only counties that had extensive cropland area were included in the study. The authors found NPP values that ranged from less than 600 g C $m^{-2}$ $yr^{-1}$ in North Dakota to over 1400 g C $m^{-2}$ $yr^{-1}$ in Iowa and Illinois. Large interannual variability in NPP (600–1400 g C $m^{-2}$ $yr^{-1}$) occurred in Iowa over the 15-yr period. The authors discussed the importance of large-scale climatic control of production in Iowa and the influence of subtle factors such as flooding and midseason droughts in addition to overall temperature or precipitation changes.

A second study computed cropland NPP for 1982–98 for 17 major crops in over 900 counties across the United States for comparison with satellite-derived estimates of absorbed radiation and NPP (Lobell et al., 2002). The authors found good agreement between the two estimates. Light-use efficiency factors were estimated for these counties from the two data sources, and spatial patterns of the roles of climate influences in the satellite-derived NPP were identified.

A third study investigated cropland area and harvest information in northeastern Colorado as part of a study of land-use change in the region. Parton et al. (Parton et al., 2003) reported decreases in cultivated land areas during 1950–2000 as the urban population increased. However, changes in agricultural management such as shifts to irrigated crops and intensified fertilization resulted in increased yields and therefore higher production in this region.

In this paper, we present a compilation and analysis of cropland dynamics over 30 yr for counties in the coterminous United States derived from USDA NASS information (USDA, 2001). Cropland area, total production, and NPP (production per cropland area) were characterized from 1972 to 2001. NPP (g C $m^{-2}$ $yr^{-1}$) is advantageous for these analyses compared to production in traditional agronomic units (e.g., bushels or tons) because 1) NPP allows a direct link to carbon cycle research, providing useful information for understanding continental-scale patterns and for an additional source of NPP data available for evaluating ecosystem models; 2) NPP provides a common unit of production among different crop types, thereby facilitating comparisons and allowing aggregation over all crop types; 3) NPP is a vital input driving soil organic matter (SOM) dynamics and net carbon exchange in these regions, and therefore is an important component of global $CO_2$ mitigation by agriculture (Paustian et al., 1998).

We use the following nomenclature in this paper. NPP is the production per unit of crop area (in units of g C $m^{-2}$ $yr^{-1}$). NPP is calculated by aggregating production ($P$) and area ($A$) across all 17 crop types used in this study. Here $P$ (total production; in units of g C $yr^{-1}$) refers to summed NPP over some geographic area (e.g., county or country):

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$$P = A \times \mathrm{NPP}. \tag{1}$$

In this study, we applied the methods of Lobell et al. (Lobell et al., 2002) and Prince et al. (Prince et al., 2001) to a longer time series and for all counties in the coterminous United States to estimate the contribution of cropland NPP to U.S. total NPP. We calculated trends in cropland NPP and area to identify the role of each in driving changes in $P$. Our estimated NPP values at the county level represent only the production associated with agricultural area within each county, and should not be interpreted as NPP for the entire county (which also includes NPP from other vegetation types such as forest).

## 2. Methods

### 2.1. NPP

The USDA NASS database includes crop production reported in various units (e.g., “tons,” “bushels”), and harvested crop area, both reported by county by year. Here we followed the methods outlined by Lobell et al. (Lobell et al., 2002) to convert these values to estimates of production for each county using the following equation:

$$P = \sum_i \frac{\mathrm{PC}_i \times \mathrm{MRY}_i \times (1 - \mathrm{MC}_i) \times C}{\mathrm{HI}_i \times f_{\mathrm{AG},i}}, \tag{2}$$

where $P$ is production (in units of g C yr$^{-1}$) and the subscript $i$ indicates different crop types. Here $\mathrm{PC}_i$ is the reported production of crop $i$ in the reported units (e.g., bushels), $\mathrm{MRY}_i$ is the mass per reported yield, and $\mathrm{MC}_i$ is the harvest moisture content (mass water/mass harvest, g/g). Here $C$ ($= 0.45$ g C g$^{-1}$) converts mass to carbon. The harvest index $\mathrm{HI}_i$ specifies the ratio of yield mass to aboveground biomass, and $f_{\mathrm{AG}}$ is the fraction of production allocated aboveground, and is directly related to the root:shoot ratio. To compute NPP, we divide $P$ by the total crop area calculated from each crop area $A_i$:

$$\mathrm{NPP} = \frac{P}{\sum_i A_i}. \tag{3}$$

Values for MRY, MC, and HI were taken from Table 1 of Lobell et al. (Lobell et al., 2002). The $f_{\mathrm{AG}}$ values were set to 0.8 following Lobell et al. (Lobell et al., 2002) except for corn (0.85), hay (0.53), wheat (0.83), sunflowers (0.94), soybeans (0.87), oats (0.71), and barley (0.67), which were taken from a synthesis by Prince et al. (Prince et al., 2001).

We analyzed the same 17 crops for the coterminous United States as Lobell et al. (Lobell et al., 2002) because they represent the crops with the most area nationwide. Production and area information are included in the NASS database annually from the early 1900s forward. Inspection of the area and production numbers revealed that not all states reported cropland area and/or production until

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the early 1970s, and for this reason, we chose our time period of interest as 1972–2001. This 30-yr record also allowed us to investigate trends in cropland area and NPP for two 15-yr intervals, 1972–86 and 1987–2001.

To determine which of NPP and/or $A$ trends drive $P$ trends, we calculated differences in variables across the study period:

$$\Delta P = P_2 - P_1 = A_2 \times \mathrm{NPP}_2 - A_1 \times \mathrm{NPP}_1. \tag{4}$$

Since $A_2 = A_1 + \Delta A$ and $\mathrm{NPP}_2 = \mathrm{NPP}_1 + \Delta\mathrm{NPP}$, Equation (4) becomes

$$\Delta P = P_2 - P_1 = (A_1 + \Delta A) \times (\mathrm{NPP}_1 + \Delta\mathrm{NPP}) - A_1 \times \mathrm{NPP}_1, \tag{5}$$

where the subscripts indicate values at two different times. Rearranging terms and dividing by $P_1$ results in

$$\frac{\Delta P}{P_1} = \frac{\Delta A}{A_1} + \frac{\Delta\mathrm{NPP}}{\mathrm{NPP}_1} + \frac{\Delta A \times \Delta\mathrm{NPP}}{P_1}. \tag{6}$$

Thus, the fractional increase in $P$ is the sum of the fractional increase in area plus the fractional increase in NPP plus an interaction term. We used 1972 and 2001 as the 2 times in the equations, and the results from the linear regression equations to specify the values used at these times.

## 2.2. Limitations of NASS

The NASS database does not include all crops in all years. Of particular concern is that crop information is available for some years but not for others since this will affect our trend analysis. Since data are originally reported at the state level, then developed for the county level, the database relies on crop information reported by each state. Therefore, there is some uncertainty when a county's area for a particular crop is zero: the information could actually be zero, or it may be that the information is missing. NASS does not report when information is missing. However, several methods were used to identify missing data.

1) The Agricultural Census is conducted every 5 yr by the USDA and is a separate and more complete database. Maps for the 1992 and 1997 censuses of crop area (USDA, 1992; USDA, 1997) were visually compared with NASS-reported area in the same years to identify locations with missing data.
2) Time series of county crop area from NASS were visually inspected to identify those counties for which the area of certain crops jumped from zero to substantial values or the reverse. This step function behavior indicated missing crop information.
3) Time series of crop area reported by NASS for all counties in a state were visually inspected. For a given crop type, in states with missing data, all counties with some crop information jumped from zero to nonzero values (or the reverse) during the same year.

Thus, for a given crop and county, if NASS reported the information in any years, we used this information to determine whether there were missing years at other

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**Table 1. Missing crops by state as determined by comparison with the 1992 and 1997 Agricultural Census.**

| Crop | States missing | Area reported by Agricultural Census (millions of acres) | Approximate total missing area in NASS (percent of area reported by Agricultural Census) |
|---|---|---|---|
| Hay (all types) | CA, MS, AR, LA, FL, ME, VT, NH, MA, CT | 57–60 | 20 |
| Potatoes | CA, NV, NE, OH, IN, TX, ME, MA | 1.3 | 25 |
| Sorghum | AZ, CA, AL, UT, MT | 8–11 | <1 |
| Barley | VA, NC, ME | 6 | <1 |
| Sugar beets | NM | 1.4 | <1 |

times (see methods 2 and 3 above). We identified when and where NASS never reported data for a given crop and county from the Agricultural Census (see method 1 above). This methodology could conceivably miss crops that were never reported by certain states in the NASS database and were not present in the 1992 and 1997 Agricultural Censuses but were present before 1992. However, even if these situations existed, the trend analysis we present would not be adversely affected, but instead would simply lack information about that particular crop.

Hay was the crop with the most amount of missing information as determined from comparisons with the Agricultural Census (Table 1). Across the coterminous United States, ~1 million acres of hay were not reported in the NASS database in 1992 and 1997, or 20% of the total. Potatoes were also missing a substantial amount of the time (25%). Sorghum, barley, and sugar beets were missing minor

**Table 2. Crops with partially reported information by state as determined by inspection of time series.**

| Crop | States (counties if $\leq 5$) missing | Total No. of counties |
|---|---|---|
| Hay (all types) | AL, IA, ID, MI, NM, NY, OR, SD, TN, TX, UT, VA, WA | 802 |
| Potatoes | MI, NM (1), OR (4), UT (1), VA (2), WA (5) | 25 |
| Corn for silage | CA, CO, ID, MD, NC, NM, NY, SD (2), UT, VA, WV, WV, WY (3) | 252 |
| Oats | AR, CA, GA, ID (2), NC (2), NY, WA (1) | 52 |
| Barley | AR (1) | 1 |
| Peanuts | NM (1) | 1 |
| Soybeans | PA, NY (3), WV (1) | 12 |
| Sugar beets | CA, CO (5), ID, MI, OR (1), WA (1) | 51 |
| Sunflower seeds | TX (1) | 1 |

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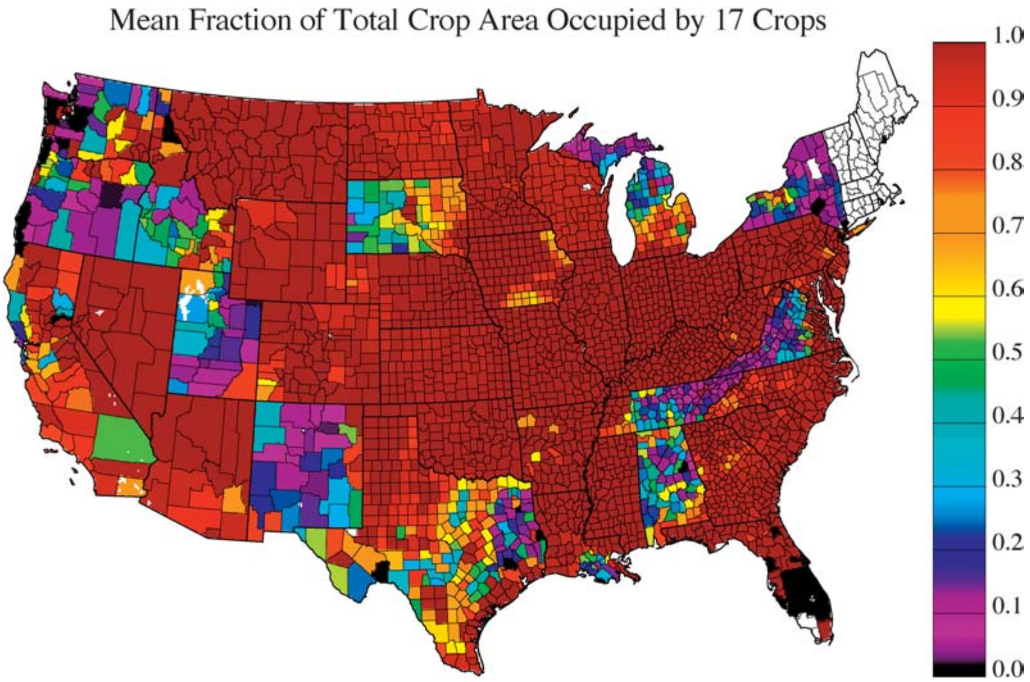

**Figure 1. Fraction of total cropland area in each county that is occupied by the 17 crops used in this study.**

amounts at the national scale. Crops with large areas of partially reported information include hay, corn for silage, oats, and sugar beets (Table 2).

There are several options to address missing information, ranging from including all available information in the NASS database to eliminating all counties in a state with any missing information. Since we were concerned that estimated crop trends could be adversely affected by missing data, we did not include information about a particular crop in a particular county if there was any missing information. For example, we included information about hay production from counties in states such as Nevada that have had continuously reported hay yields, but discarded hay data from counties in states such as Texas that reported hay during some years but not others. (Of course, we could not include information on crops in states that never reported that crop, such as hay in California.) Thus, not all production from a given crop type may be included, but information for any crop type included for a county was complete during 1972–2001.

To identify those counties having partially reported data and to get a sense of how important those data might be to the county's total production estimate, we plotted the percentage of cropland area considered in this study compared with the total cropland area reported in the NASS database averaged across years (Figure 1). This map highlights counties that either had partially reported information for a particular crop, which we did not include, or substantial area associated with crops other than the 17 major types. The map does not include information completely missing from the NASS database (Table 1). We only considered crops that contributed at least 20% individually to the total county production.

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The 17 crops reported for all years make up over 97% of the cropland area in the vast majority of U.S. counties. In the few counties that had over 10% area devoted to crop types other than the 17 we studied, the additional area was associated primarily with sugar cane (Louisiana), rye (the northern Great Plains), pima cotton (the Southwest), and beans (the western states and Michigan). About 20 states had some partially reported crop information. In most of these states, missing hay data were responsible for the largest fraction of lost production. Notable exceptions included California, which reported no hay (see Table 1), but partially reported oats, sugar beets, and corn for silage; and Arkansas, which also reported no hay but partially reported oats.

States with substantial agricultural production that have missing or partially reported information include South Dakota, Iowa, Oregon, Washington, California, and Texas. Other states that have cropland area missing but relatively small total area and production include Alabama, Tennessee, Virginia, New York, Michigan, and Utah. The majority of these unreported data were associated with hay. Counties in these states that have large area associated with the missing or partially reported crops could have different NPP and $P$ behavior once the missing data are incorporated.

Crop information for states in the extreme Northeast (Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont) is not included in the NASS database. In addition, data for perennial crops such as fruit were not considered in this work.

## 3. Results

### 3.1. Crop information in 1997

As examples of our estimates of cropland area, NPP, and $P$, we show maps from 1997 in Figure 2. Cropland area (for the 17 selected crops) ranged from 0 to >3500 km$^2$ (Figure 2a). Regions with large cropland area included Midwestern and Great Plains states across to Montana, the Mississippi River Valley, and several counties in the western states.

On a per-area basis, NPP was highest in the West (>800 g C m$^{-2}$ yr$^{-1}$; Figure 2b) with only slightly lower values in the central United States, especially Nebraska, Illinois, and Iowa, as well as in scattered counties across the United States.

Total production ($P = \text{NPP} \times A$) was highest in the Midwest, northern Great Plains, Mississippi River Valley, and parts of Washington, Idaho, and Montana (Figure 2c), where large cropland areas and high NPP was reported. Some counties exhibited relatively high $P$ due to either large cropland area or large NPP, but not both. The central valley of California demonstrates this: in the northern valley, counties had high NPP but smaller area, while in the southern region, the reverse occurred.

### 3.2. Aggregated U.S. information

We summed $P$ and cropland area over all counties in the coterminous United States and computed nationwide NPP. The U.S. cropland area remained relatively

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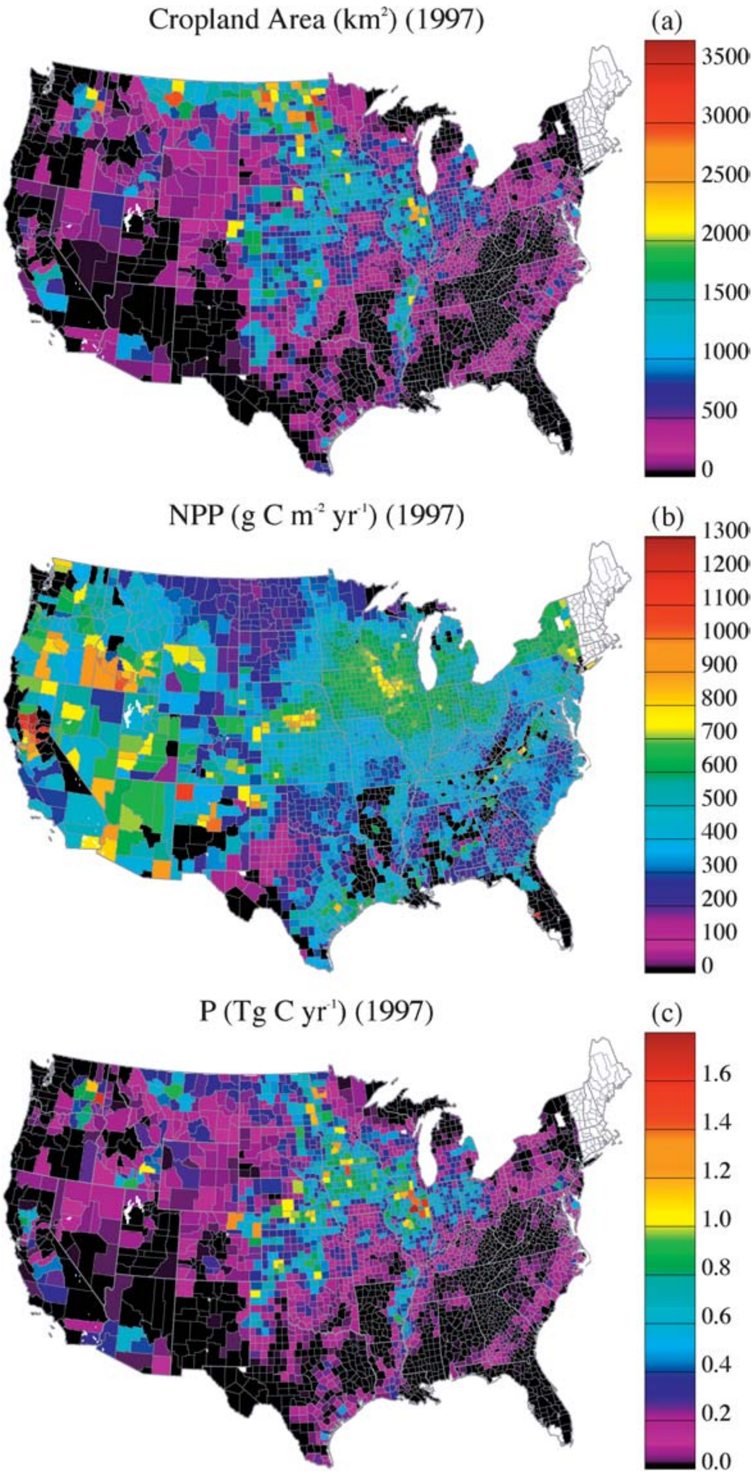

**Figure 2.** (a) Cropland area, (b) NPP, and (c) production from 1997 for the 17 crops used in this study. Counties in white had no cropland area during the period of interest.

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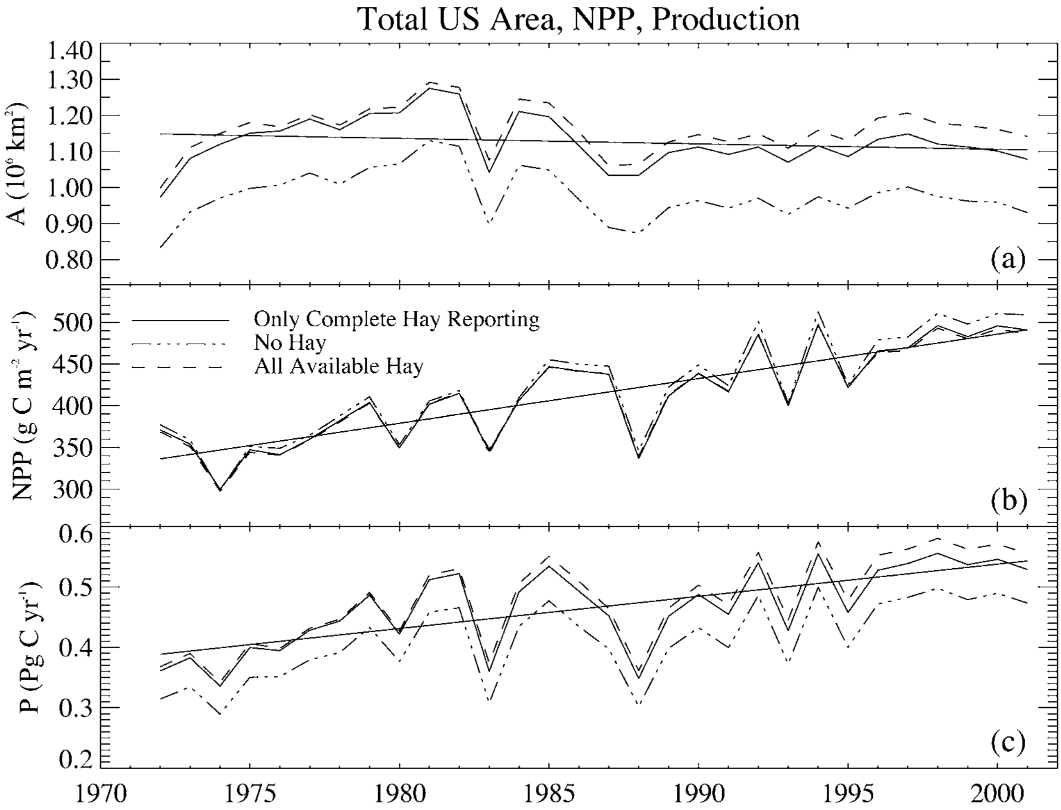

**Figure 3. (a) Total area ($10^6$ km$^2$), (b) mean NPP (g C m$^{-2}$ yr$^{-1}$), and (c) total production (Pg C yr$^{-1}$) in the coterminous United States from 1972 to 2001. Plotted are values for the case where only crops with complete reporting were included (solid curve); for the case where no hay information was included (dotted–dashed curve); and for the case where all available hay information was incorporated, including counties with only partially reported records (dashed curve). Trend lines shown for the case of only crops with complete reporting.**

**Table 3. Coterminous U.S. trends in NPP, cropland area, and total production.**

| | Only counties with complete hay records | | All available hay information | No hay included |
|---|---|---|---|---|
| Variable | Trend | Percent increase over 1972 | Trend | Trend |
| NPP (g C m$^{-2}$ yr$^{-2}$) | 5.3* | 46 | 5.8* | 5.3* |
| $A$, area (km$^2$ yr$^{-1}$) | −0.0015 | −4 | −0.0015 | 0 |
| $P$, production (Pg C yr$^{-2}$) | 0.0053* | 40 | 0.0050* | 0.0061* |

* Trend significantly different from 0 ($p < 0.001$).

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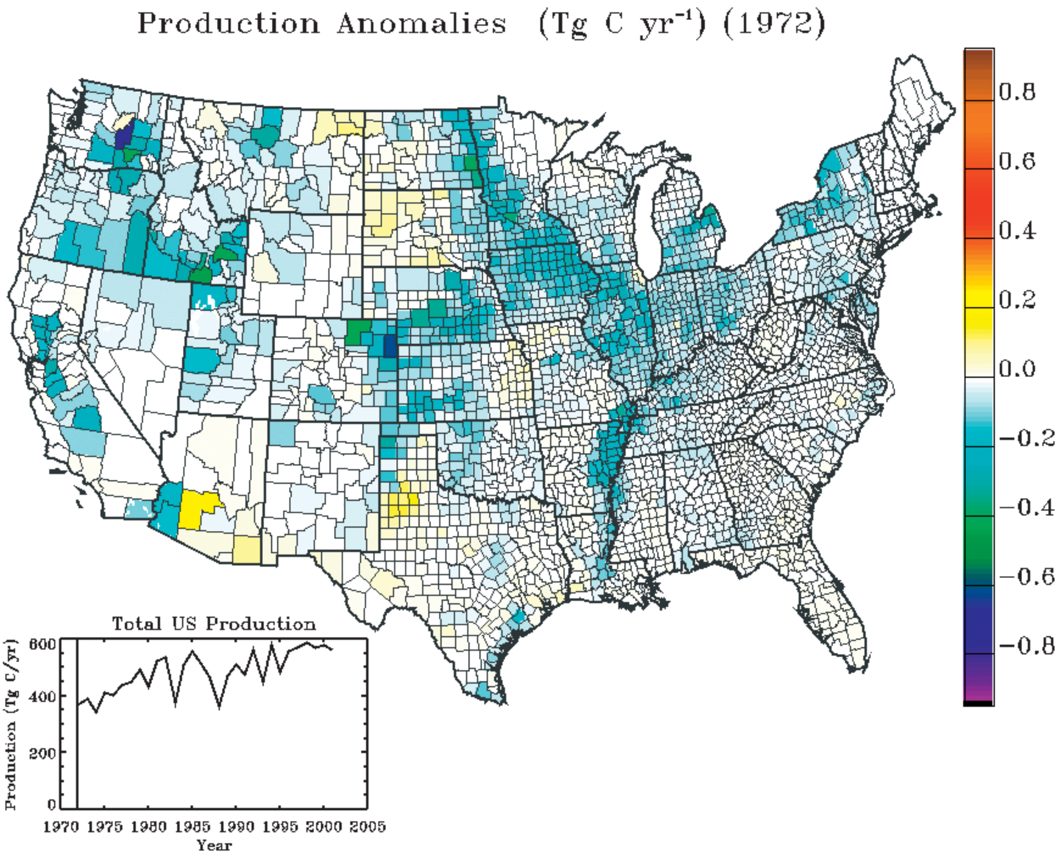

**Figure 4. Animation of county production anomalies (Tg C $yr^{-1}$) from 1972 to 2001. Inset shows total coterminous U.S. production.**

constant over the 30-yr period with a mean value of $1.1 \times 10^6$ $km^2$ (Figure 3a). We computed a slightly negative trend that corresponded to a decrease of 6% over the time period (Table 3). This behavior has been previously reported by the USDA's Census of Agriculture (USDA, 1992). In contrast to area, NPP increased over the period with values of ~350 g C $m^{-2}$ $yr^{-1}$ in 1972 and ~490 g C $m^{-2}$ $yr^{-1}$ in 2001. This gain of 140 g C $m^{-2}$ $yr^{-1}$ over 30 yr represents an increase of 40%. Total U.S. production increased during 1972–2001 from 0.37 to 0.53 Pg C $yr^{-1}$ (a 40% increase).

We found substantial interannual variability in total production ($P$) of the United States. For example, $P$ decreased by 0.2 Pg C $yr^{-1}$ from 1982 to 1983, or a change of ~50%. Variability in these years was driven by changes in both NPP and area. Somewhat lower variability in $P$ occurred in the mid-1990s, and these smaller variations were primarily driven by changes in NPP.

An animation of annual $P$ anomalies (Figure 4) reveals that the Great Plains and Midwest regions had large interannual variability that drove much of the U.S. total interannual variability. Other counties in western states such as Washington, Oregon, California, and Arizona also influenced the U.S. total production. These

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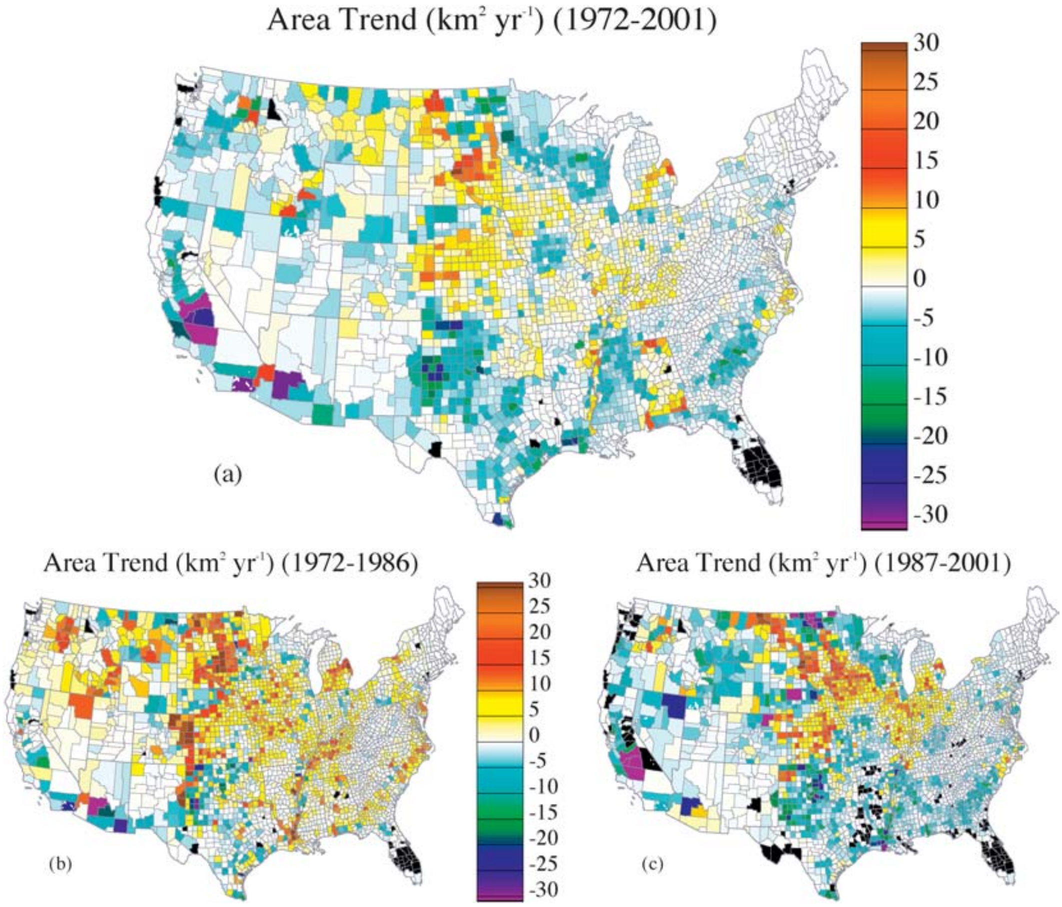

Figure 5. Trends in cropland area from (a) 1973–2002, (b) 1973–87, and (c) 1988–2002. Counties in black had no crop area during the period of interest. Color scale in bottom middle applies to (b) and (c).

areas made up the majority of U.S. production and therefore exerted the most effect. Many regions exhibited spatial correlation in the production anomalies, suggesting that large-scale forcing mechanisms such as climate or economic conditions drove year-to-year variability in production.

## 3.3. County-level results

Most of the United States had little change in cropland area from 1972 to 2001 (Figure 5a), including those regions with substantial cropland area (see Figure 2). Relatively large increases in area occurred in South Dakota as well as in other counties scattered across the country. Declines in cropland area occurred in California, Arizona, and Texas, and in counties of the northern Great Plains region and the Southeast.

In the first half of the record, cropland area increased dramatically in counties in Washington, Colorado, Idaho, and the northern Great Plains (Figure 5b). Major

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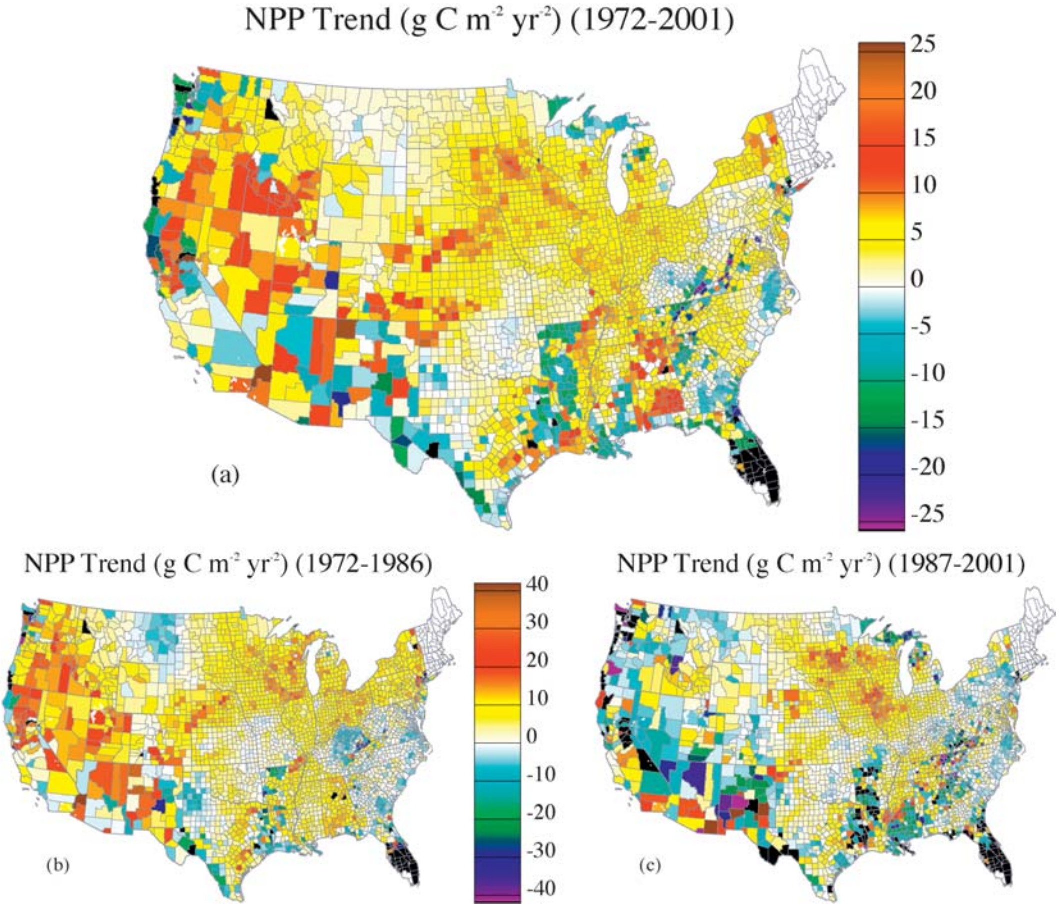

**Figure 6. Same as in Figure 5 but for NPP (g C $m^{-2}$ $yr^{-1}$).**

decreases occurred in the Southwest and Texas during this period. From 1987 to 2001, counties in the Great Plains exhibited the largest increases (Figure 5c). Relatively large decreases in this time period occurred in counties throughout the United States.

Trends in cropland NPP were positive throughout much of the United States (Figure 6a), in particular, in western counties and in Alabama, where NPP increased by 150–600 g C $m^{-2}$ $yr^{-1}$. Much of this gain occurred in the first half of the record, but in the central United States, increases occurred in both halves of the record (Figures 6b and 6c). Decreases in NPP occurred in Texas and other southern and western states. Many of these counties with the largest positive trends actually had cropland area increase from zero during the time period, causing NPP to increase from zero. Similarly, the largest negative NPP trends were associated with counties whose cropland area declined to zero during the time period.

Large $P$ increases occurred across the Great Plains and Midwest regions (Figure 7a) with gains of 0.75 Tg C $yr^{-1}$ over the 30 yr. In Colorado, these changes

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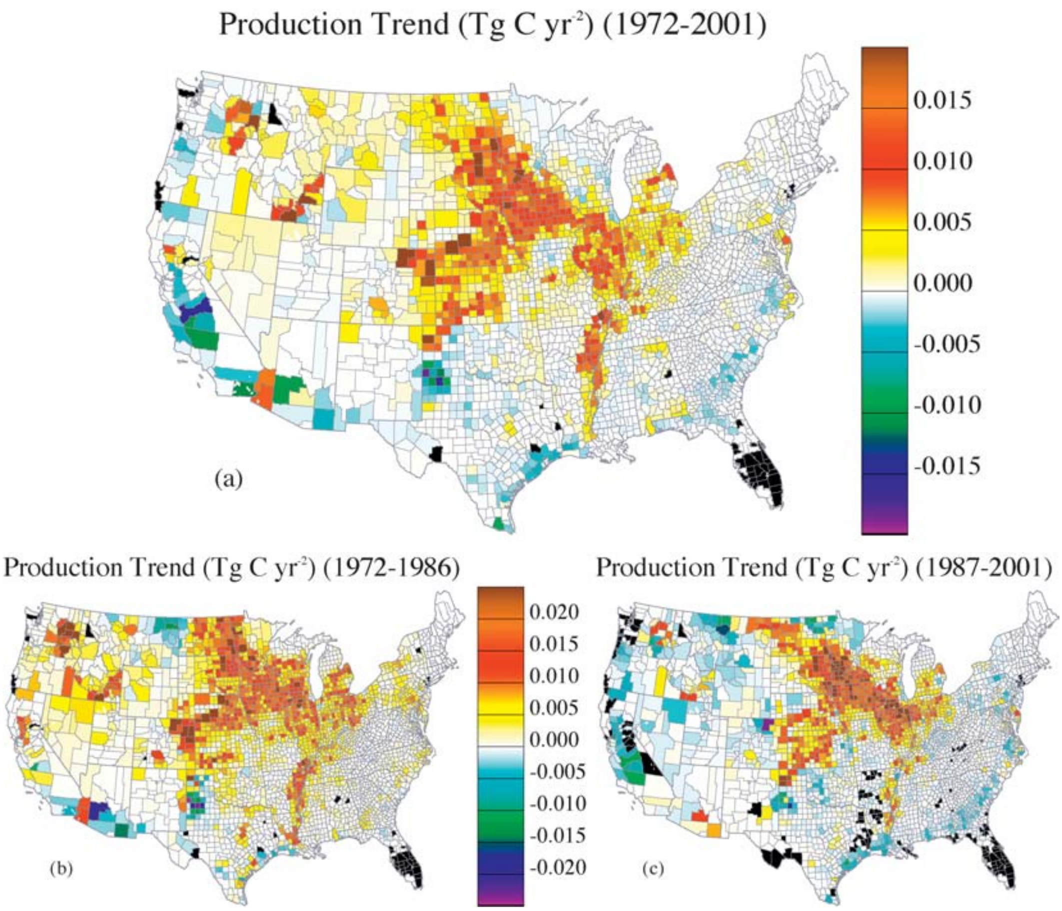

**Figure 7. Same as in Figure 5 but for production (Tg C yr$^{-1}$).**

happened primarily in the first 15 yr, whereas increases farther east were large in both time periods (Figure 7c). Substantial gains also occurred in Washington, Idaho, and Arizona, which in contrast to the Great Plains region, occurred in the first half of the time period (Figure 7b). Large decreases in production were evident in California and northern Texas.

## 3.4. Determining where NPP and/or *A* trends drove *P* trends

Because $P$ is the product of NPP and area ($A$), we investigated NPP and $A$ trends to identify which of the two variables most influenced $P$ by county. To do so, we analyzed Equation (6) for each county, utilizing the increase in each of the three variables over the 30 yr as determined from the least squares regression line (Figure 8). Percent increases enhance counties that had lower overall values compared to trends (Figures 5–7), although positive/negative patterns remain the same. Percent increases less than −100% (i.e., large percent decreases) were an

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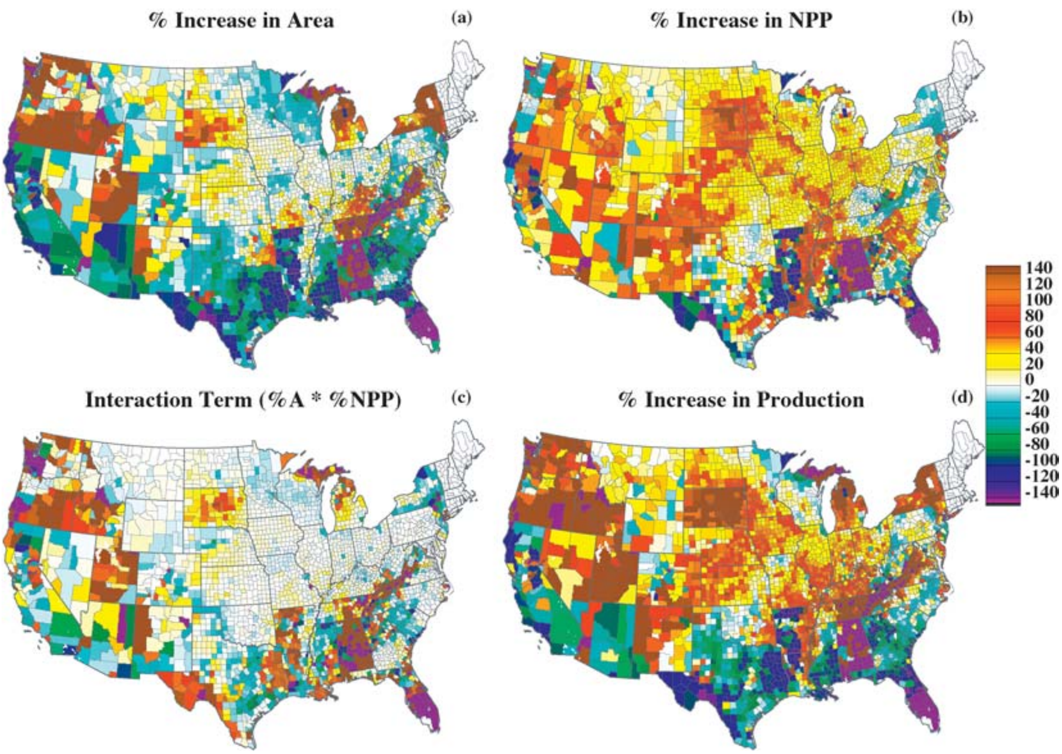

Figure 8. Percent increases from 1972 to 2001 (over 1972 values) for (a) area, (b) NPP, (c) the interaction term, and (d) production (see Equation (6)).

artifact of using values predicted by the least squares regression line and indicated that values dropped to zero during the record.

Percent area gains ranged from a doubling or more of cropland area in South Dakota, Alabama, and counties in other western states to more than 50% decreases across the West and South. Percent increases in NPP exceeded 20% throughout much of the United States. Large gains occurred in the Great Plains region and in counties across the West, where NPP doubled over 30 yr. Counties in the Southeast also had large percent gains, though the overall production in these states is minimal (see Figure 2). The interaction term was greatest in states in the West, South Dakota, Michigan, New York, and the Southeast, highlighting counties that had large changes in both NPP and cropland area. Percent changes in production were highest in the counties across the West, Great Plains, Michigan, and New York. Fifty percent or higher decreases in production are evident in the southern states from California to the East Coast.

## 4. Discussion

Our 1992 NPP estimates exhibited similar values and patterns to those shown by Prince et al. (Prince et al., 2001). The highest NPP in the Midwest region was 800 g C $m^{-2}$ $yr^{-1}$ in Iowa and Illinois and decreased to 200 g C $m^{-2}$ $yr^{-1}$ in North

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Dakota. We also computed similar interannual variability in Iowa NPP to that reported by Prince et al. (Prince et al., 2001) (see our Figure 4). For example, 1992 and 1994 were years when NPP was reported as high by Prince et al. (Prince et al., 2001), and 1983, 1988, and 1993 were low years. This behavior was reflected in our estimates and, in fact, was representative of the characteristics of the U.S. total production in those years.

Our estimates of total U.S. cropland production ranged from 400 to 600 Tg C $yr^{-1}$. This is close to that estimated by Lobell et al. (Lobell et al., 2002; 550–650 Tg C $yr^{-1}$), who used satellite-derived NPP for croplands computed using two light-use efficiencies, one for corn and one for other crop types combined.

Large interannual variability in production seen in Figures 3 and 4 was likely driven by changes in climate. Recent studies have analyzed the response of crop production to the El Niño–Southern Oscillation (Izaurralde et al., 1999; Phillips et al., 1999), and the effects of the 1982/83 event can been seen. In addition, other climate influences can be identified: the 1988 drought and the extensive flooding in the Midwest and Great Plains in 1993. Although we feel that climate was a major driver of variability, other influences such as economic decisions and management decisions (e.g., increases in irrigation) were also likely influences. Further research is required to quantify the contribution of each of these processes.

The large $P$ increases shown in Figure 7 were primarily due to increases in NPP. Increases in $A$ also contributed in counties of central South Dakota and to a lesser degree in Nebraska, Kansas, and Colorado. In Washington, Idaho, and Arizona, counties had larger production resulting from increases in both area and NPP. Most of the counties that experienced large decreases in $P$ had decreases in cropland area. One exception was northern Texas, which exhibited decreases in both NPP and area.

At the national level, and generally at the county level, gains in production resulted from gains in NPP. Note that NPP can change for several reasons.

1) Shifts to different crops: If farmers replace wheat with more productive corn, for example, overall NPP increases and thus $P$ increases.
2) Management practices: Higher yielding varieties, fertilization, irrigation, and better pest management all could contribute to increased NPP.
3) Climate: Changes in temperature, precipitation, or solar radiation may result in NPP gains. A study by Lobell and Asner (Lobell and Asner, 2003) highlighted the importance of decadal trends in climate on crop yields.
4) Economics: Changing demand and shifting prices impact farmers' decisions about planting different crop types (see reason 1 above) and affect management practices (see reason 2 above).
5) Accuracy: Because NASS estimates annual cropland area and production by surveying a subsample of farms, the representativeness of this subsample could influence NPP estimates. NASS reports relative confidence intervals for grain stocks and acreage for major crops in the United States. The 95% confidence interval for corn stocks in 2003 was ±6.4%; values for wheat, oats, and barley were smaller; whereas values for soybeans (±12.6%) and sorghum (±29.7%) were larger. At the

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> national level, corn represents more than 40% of production, soybean 13%, and sorghum 5%; these proportions clearly change for individual counties. Thus, it is possible that some interannual variability could result from sampling errors, but the largest anomalies are likely driven by the factors listed above. Furthermore, results from the Census of Agriculture, a complete survey conducted every 5 yr, are used to update the NASS annual information when appropriate (USDA, 2001), implying that actual NPP trends were likely to be well represented in the annual reports.

At the county level, changes in area and production shown here may reflect a shift to crops that are either missing from the NASS database or only partially reported and therefore not included in our study. For example, in counties in southern Washington, the decreases in area represented a shift to hay, which was not included in our analysis due to partial reporting.

Prince et al. (Prince et al., 2001) reported minimal sensitivity of their NPP calculations to root:shoot ratios, but a higher sensitivity (10%) to a range of the harvest index (HI). The authors report that the interannual variability in cropland NPP greatly exceeds the uncertainty associated with parameters. These results also apply to our study.

Our calculations assumed a fixed harvest index throughout the study period. Accounting for any increase in HI in Equation (2) would reduce our estimates of production trends. Although the harvest index for wheat and barley increased dramatically in the 1900s, little discernible trend occurred during our study period (Hay, 1995). The harvest index of corn has remained relatively constant during the last century (Hay, 1995; Sinclair, 1998). Thus, for three of the most widespread crops, it is likely that changes in harvest index played a minor role in increasing harvested yields. Investigating this effect further will require additional research that quantifies historical changes in HI across a variety of crop types.

Ground-based estimates of NPP provide important tools for evaluating terrestrial ecosystem models. The Global Primary Production Data Initiative (GPPDI) is a major effort under way to compile data for such use (Zheng et al., 2003). Our cropland NPP estimates augment this initiative by providing data from additional counties beyond what is currently available [Iowa and parts of Minnesota from Prince et al. (Prince et al., 2001)]. In addition, these time series can be used for comparisons of interannual variability of production (e.g., Lobell et al., 2002).

## 5. Conclusions

By utilizing annual estimates of cropland yields and area over 30 yr across the United States, we investigated changes in cropland production and assessed the contribution of NPP and area to production. Our study extends recent research (Lobell et al., 2002; Parton et al., 2003; Prince et al., 2001) by including additional years, crops, and counties, and therefore is a unique analysis of crop production dynamics.

Most of the U.S. agricultural production, as measured by net primary production, is concentrated in the Great Plains and Midwest regions. Other regions that contributed included counties in the West and Mississippi River

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Valley. Most counties across the United States reported some production, but the majority contributed little to the national total.

Over the 30-yr time span, total U.S. agricultural production (g C $\mathrm{yr}^{-1}$) increased by 40% for the 17 crops we studied. This increase is attributed mainly to increased NPP (g C $\mathrm{m}^{-2}$ $\mathrm{yr}^{-1}$), as total U.S. cropland area remained relatively constant. Gains in NPP were likely due to several reasons, including more effective fertilization and pest management, higher yielding cultivars, more favorable climate, shifts to productive crop types (e.g., wheat to corn), and economic factors (Duvick and Cassman, 1999; Evans, 1997; Lobell and Asner, 2003). Substantial interannual variability in total U.S. production occurred, driven by changes in crop production in the Midwest, Great Plains, and counties in the West.

Different counties exhibited different NPP, $A$, and $P$ behavior during 1972–2001. Notable patterns include the following.

- Large production increases across the Midwest, northern and western Great Plains, and along the Mississippi River Valley. Increased NPP across this region was responsible for these large $P$ changes with little or no change in cropland area.
- Large production increases in scattered counties in Washington, Oregon, Idaho, Arizona, and Michigan, which were driven by additional cropland area as well as by increased NPP.
- Decreases in production across the southern United States with the largest occurring in California and Texas. These were a result of reductions in cropland area.

We computed a 40% increase in net carbon fixed by agricultural crops in the United States. What is the fate of this carbon? Several possibilities exist. Crop residues left over after the harvest decompose and move carbon to soil organic matter. Increases in the amount of carbon transferred from the atmosphere to plants, as reflected in changes in production, therefore increase the flux to longer-term soil carbon pools. Larger C fluxes to soil potentially speed the recovery of C in agricultural soils, which has implications for mitigating future sources and sinks of C in the United States.

Another possible fate is related to the harvested mass. This mass could be consumed and respired locally, or it could be transported across the country or exported to other countries. Transportation and export effects appear as sinks in atmospheric inversion modeling studies and must be accounted for when interpreting such results (Pacala et al., 2001).

In future research, we plan to assess how shifts among crop types and management practices (e.g., irrigation) have influenced our estimated NPP trends. In addition, the dataset presented here will be combined with satellite-derived NPP to evaluate the contributions of cropland NPP and area changes to regional- and continental-scale NPP trends.

**Acknowledgments.** We thank Mark Easter, Steve Williams, and Keith Paustian for assistance with the NASS database. Two anonymous reviewers provided comments that improved the manuscript. This work was funded by NASA EOS Grants NAG5-9356 and NAG5-9462, NASA NIP Grant NAG5-8709, and an NSF Graduate Research Fellowship. This is CIW Department of Global Ecology Publication Number 38.

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