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# Nitrogen use efficiency and crop production: Patterns of regional variation in the United States, 1987–2012

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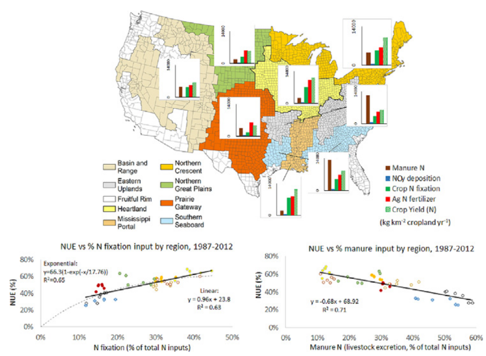
## HIGHLIGHTS

- NUE decreased in a majority of regions in the US from the decade 1987–97 to 2002–12.
- Cropland area generally decreased & mineral fertilizer increased over the same period.
- Response of crop production to nitrogen inputs varies regionally across the country.
- Patterns differ depending upon whether cropland area or total area scaling is used in each region.

## GRAPHICAL ABSTRACT

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## ABSTRACT

National-level summaries of crop production and nutrient use efficiency, important for international comparisons, only partially elucidate agricultural dynamics within a country. Agricultural production and associated environmental impacts in large countries vary significantly because of regional differences in crops, climate, resource use and production practices. Here, we review patterns of regional crop production, nitrogen use efficiency (NUE), and major inputs of nitrogen to US crops over 1987–2012, based on the Farm Resource Regions developed by the Economic Research Service (USDA-ERS). Across the US, NUE generally decreased over time over the period studied, mainly due to increased use in mineral N fertilizer above crop N requirements. The Heartland region dominates production of major crops and thus tends to drive national patterns, showing linear response of crop production to nitrogen inputs broadly consistent with an earlier analysis of global patterns of country-scale data by Lassaletta et al. (2014). Most other regions show similar responses, but the Eastern Uplands region shows a negative response to nitrogen inputs, and the Southern Seaboard shows no significant relationship. The regional differences appear as two branches in the response of aggregate production to N inputs on a cropland area basis, but not on a total area basis, suggesting that the type of scaling used is critical under changing cropland area. Nitrogen use efficiency (NUE) is positively associated with fertilizer as a percentage of N inputs in four regions, and all regions considered together. NUE is positively associated with crop N fixation in all regions except Northern Great Plains. It is negatively associated with manure (livestock excretion); in the US, manure is still treated largely as a waste to be managed rather than a nutrient resource. This significant regional variation in patterns of crop production and NUE vs N inputs, has implications for environmental quality and food security.



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## 1. Introduction

As noted by several recent studies (Robertson and Swinton, 2005; Billen et al., 2013; Erisman et al., 2013) the rise in global agricultural production over the last several decades has had corresponding environmental costs, including eutrophication of coastal waters and other water quality problems (Sutton et al., 2011; Davidson et al., 2011) associated with the increased use of nitrogen (N) fertilizer and increased livestock production (Howarth et al., 2002; Howarth, 2008; Bouwman et al., 2013). While crop yields have risen over the last several decades, especially in developed countries, efficiency of crop production is a continuing topic of concern (Cassman et al., 2002; Tilman et al., 2002, 2011; Clark and Tilman, 2017). Results of inefficient N uses include the environmental impacts of greenhouse gas emissions, nutrient loads to inland and coastal waters, and associated effects (West et al., 2014). Using national-scale FAO data, Lassaletta et al. (2014) examined trends in N use in world cropping systems for 124 countries, evaluating changes over the last fifty years associated with management practices, climate and other factors. Their analysis suggests that higher N use efficiency (NUE) occurs in those countries in which symbiotic N fixation is a relatively large proportion of total N inputs. In contrast, those countries relying on a high proportion of synthetic N fertilizer show a relatively low NUE. The work shows that, as a result, the agricultural production systems of different groups of countries have developed in different ways, some showing environmental improvements, and others showing declines. The analysis complements the approach of using the net anthropogenic nitrogen inputs (NANI) approach to estimate N inputs to watersheds and other regions (Howarth et al., 1996; Howarth et al., 2006; Howarth et al., 2012; Boyer et al., 2002, Hong et al., 2013, etc.) in that Lassaletta et al. focuses on cropping systems on agricultural lands rather than the entire N mass balance, including direct impacts of human consumption.

While national-level analyses are appropriate for international comparisons addressing large-scale environmental policy issues, they do not address the regional variation of agriculture that occurs within a country. As indicated by Le Noë et al. (Le Noë et al., 2017; Le Noë et al., 2018), agricultural production and associated environmental impacts can be expected to vary significantly across regions within a country because of regional differences in crops, livestock, climate, resource use and production practices. This is likely to be especially true in large countries like the United States. Here, we investigate regional variation of aggregate production of major crops, nitrogen use efficiency and related factors in the United States.

NANI has been used primarily as an estimate of nutrient inputs for watersheds to assess the importance of these as a driver of riverine N fluxes in the context of other factors, including climate and hydrology (Howarth et al., 1996; Howarth et al., 2006; Howarth et al., 2012; Boyer et al., 2002; Schaefer et al., 2009; Schaefer and Alber, 2007; Han and Allan, 2008; Swaney et al., 2012; Goyette et al., 2016; Sinha and Michalak, 2016; Hong et al., 2012; Hong et al., 2013; Hong et al., 2017). Toward this end, we have developed the NANI toolbox (Hong et al., 2011) to facilitate estimating NANI at the county or hydrologic unit scale from available US agricultural and census datasets. We have also developed a variant of this tool for use with European databases, and have applied it to Northern Europe (Hong et al., 2012; Hong et al., 2017). Anthropogenic N inputs estimated using the NANI toolbox have been used to assess the regional variability of N inputs in relation to riverine N fluxes and other factors in the United States (Hong et al., 2013; Sinha and Michalak, 2016). Here, we use it to examine nitrogen inputs in relation to production and nitrogen use efficiency in relation to the major inputs of nitrogen in the US at regional levels, adopting a methodology based in part on Lassaletta et al., 2014, and using data originally employed to estimate NANI at the county level across the continental US (Hong et al., 2011; Hong et al., 2013). The variables examined are not NANI per se, but components of NANI or subsidiary variables obtained from the NANI. The aims of this work are threefold:

- To examine relationships between aggregate crop production and N use at regional scales to determine how the patterns of agricultural production, NUE, and their relationship to various N inputs vary regionally and over time.
- To determine whether patterns observed by Lassaletta et al. (2014) based on national-scale analysis across the globe apply to major regions of the US.
- To extend the results of our earlier work with the NANI toolbox, using updated agricultural census and fertilizer use information, and apply the derived data to NUE-related questions to demonstrate its utility in the realm of policy-related questions.

## 2. Material and methods

### *2.1. Aggregate crop yield, nitrogen use efficiency and related variables*

Lassaletta et al. (2014) evaluated temporal trends in several variables using national statistics from the FAO for the countries studied, including:

- The nitrogen content of crop production ("Y", for "yield" on a per-cropland area basis);
- The nitrogen input to agricultural systems, comprising the inputs of N fertilizer, manure N, N fixation by crops, and atmospheric deposition of N, termed "I", for inputs (Lassaletta et al. called this "F");
- Nitrogen use efficiency, or "NUE", defined as the ratio Y/I.

Y represents the sum of production of all major crops, expressed in terms of the nitrogen content of production divided by total cropland area, to assess the aggregate effect of nitrogen inputs on major crop production. Lassaletta et al. express the variables Y, I and I-Y on a kg-N/area basis, where the area is the cropland area of a country. As such, the relationship expresses the agronomical response of major crops to fertilization in all forms of soil N inputs, thus reflecting the fertility of the particular pedoclimatic conditions of the region. As part of their analysis, Lassaletta et al. fit functions to the data to facilitate categorizations and comparisons, and to structure the discussion in terms of the trajectory of agronomic variables of various countries, relative to hypothetical asymptotic responses. As discussed below, we restrict most of our analysis to simple linear relationships.

### *2.2. Crop data and categories considered*

The crop production and NUE assessments made here require evaluation of the nitrogen content of crop production for major crops. The crops used in the analysis are major crop categories reported in the US Census of Agriculture at the county level at five-year intervals (Table S1) and represent the standard set of crops used in the NANI toolbox (Hong et al., 2011, 2013). Following Lassaletta et al. (2014) pastureland was excluded, except for cropland pasture. For each crop, the N content of production is estimated following Hong et al. (2011) and nutrient content information from Lander et al. (1998). Total cropland area was also obtained from the Census of Agriculture at the county level. Y is calculated by summing the N content of crops of the major crop categories, aggregating to the desired level by summing the county value over multi-county regions or subregions, and normalized by dividing by the total reported cropland area at the same level of aggregation to obtain an estimate of the N content of the aggregate yield of major crops. In addition, we normalized N in aggregated crop production on a total area basis (termed Y′), in order to determine the impact of changing cropland area on the calculation of Y and total N inputs. Total area also was used to normalize N input variables (termed I′) at the subregion scale (discussed below), or summed over subregions and regions to obtain corresponding estimates normalized at these scales of aggregation. In contrast to the Y vs I relationship, which reflects aggregate crop