2020

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Tenorio, Fatima A.M.; McLellan, Eileen L.; Eagle, Alison J.; Cassman, Kenneth G.; Andersen, Daryl; Krausnick, Marie; Oaklund, Russell; Thorburn, John; and Grassini, Patricio, "Benchmarking impact of nitrogen inputs on grain yield and environmental performance of producer fields in the western US Corn Belt" (2020). *Agronomy & Horticulture -- Faculty Publications*. 1342.
https://digitalcommons.unl.edu/agronomyfacpub/1342

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Agriculture, Ecosystems and Environment 294 (2020) 106865

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Benchmarking impact of nitrogen inputs on grain yield and environmental performance of producer fields in the western US Corn Belt

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ARTICLE INFO

Keywords:
Maize
Yield
Nitrogen
Nitrogen balance
Fertilizer

ABSTRACT

Benchmarking crop yields against nitrogen (N) input levels can help provide opportunities to improve N fertilizer efficiency and reduce N losses on maize in the US Corn Belt by identifying fields most likely to benefit from improved N management practices. Here, we evaluated a large producer database that includes field-level data on yield and applied N inputs from 9280 irrigated and rainfed fields over a 7-year period (2009–2015) in Nebraska (USA). A spatial framework, based on technology extrapolation domains, was used to cluster each field into spatial units with similar climate and soil type that represent 1.3 million ha of US farm land sown annually with maize. Three metrics were employed to evaluate agronomic and environmental performance: partial factor productivity for N inputs (PFP_N, ratio between yield and N inputs), N balance (difference between N inputs and grain N removal), and yield-scaled N balance (ratio between N balance and yield). Nitrogen inputs included N from fertilizer and N contained in applied irrigation water. Average yield and N inputs were 40 and 44% higher in irrigated *versus* rainfed fields. The N balance was *ca.* 2-fold greater in irrigated *versus* rainfed fields (81 *versus* 41 kg N ha^{-1}). Of the total number of field-years, 58% (irrigated) and 15% (rainfed) had N balance $\geq$ 75 kg N ha^{-1}, which was considered a threshold to identify fields with potentially large N losses. Very large ($>$ 150 kg N ha^{-1}) and negative N balance estimates were not apparent when analysis was based on field averages using a minimum of three years' data instead of individual field-years. Nitrogen balance was smaller for maize crops following soybean compared to continuous maize. Despite the larger N balance (on an area basis), irrigated fields exhibited smaller yield-scaled N balance relative to rainfed fields. The approach proposed here can readily be adopted to benchmark current use of N fertilizer for other cereal-based crop systems, inform policy, and identify opportunities for improvement in N management.

1. Introduction

Nitrogen (N) is an essential nutrient to support crop growth and a key pillar for global food security (Cassman et al., 2002; Tilman et al., 2002; Mueller et al., 2012). Sources of N that contribute to crop N supply include synthetic fertilizer, organic fertilizer such as animal and green manure, biological N fixation, mineralization of soil organic matter, dry and wet atmospheric deposition, nitrate-N (NO_3^--N) in shallow water tables, and, in the case of irrigated agriculture, N contained in applied irrigation water (Skaggs et al., 1995; Connor et al., 2011). Synthetic N fertilizer accounts for *ca.* half of total N input to global cropland, and increasing N fertilizer use since the middle of the 20th century has been a major contributor to rapid increases in cereal crop yields (Cassman et al., 2002; Tilman et al., 2002; Foley et al., 2011). Nitrogen inputs exceeding crop N requirements (*i.e.,* N surplus) can lead to large N losses *via* denitrification, leaching, volatilization, and run-off, straining the capacity of the earth to meet humanity's need for clean water, clean air, and abundant and healthy food (Matson

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https://doi.org/10.1016/j.agee.2020.106865
Received 14 September 2019; Received in revised form 8 February 2020; Accepted 11 February 2020

et al., 1998; Erisman et al., 2013; Steffen et al., 2015). In contrast, N fertilizer inputs consistently below crop N requirements (*i.e.,* N deficit) can lead to soil N mining and reduced soil quality (Sanchez, 2002; Sanchez and Swaminathan, 2005). The challenge is to find an effective balance between N inputs and crop N requirements, to achieve high crop productivity while preserving soil quality and reducing environmental footprint (Zhang et al., 2015; Lassaletta et al., 2014).

Benchmarking N input use in individual fields for a large number of cohort fields may help identify fields with greatest opportunities to improve productivity and reduce overall environmental impact. However, we are not aware of previous studies that used actual field-level data to benchmark the efficacy of N inputs to produce grain while minimizing N losses to the environment. Instead, studies addressing both productivity and environmental performance of agro-ecosystems in relation to N inputs can roughly be grouped in two categories. The first category includes the large number of studies conducted in experimental plots or field trials in which researchers selectively applied different N input levels or management practices and carefully measured yield and N losses (*e.g.,* Harmel et al., 2008; Venterea et al., 2012). The second category includes *in-silico* modeling studies at regional and global levels (*e.g.,* Van Drecht et al., 2003; Howarth et al., 2006). In between these two extremes, we found few studies that explicitly aimed to benchmark on-farm yield and N input use (*e.g.,* Khanal et al., 2014; Lassaletta et al., 2014; Basso et al., 2019). However, most of these studies have relied on N fertilizer use data reported at a high level of spatial aggregation (*e.g.,* country, state). The major reason for scarcity of field-level studies is lack of producer data on yield and N inputs. For example, for the Corn Belt, a large region in the north-central USA that produces *ca.* one third of global maize production, data on N fertilizer rates applied to maize are available only at the state level, and at 5-year intervals (USDA-ERS, https://data.ers.usda.gov/reports.aspx?ID = 17883). Due to the lack of more detailed data, some studies have attempted to generate predictions of N fertilizer for small regions or even individual fields following tortuous methods (*e.g.,* fertilizer sales records, university-based N recommendations), but such predictions have not been validated for their ability to reproduce actual N fertilizer rates in producer fields (Khanal et al., 2014; Basso et al., 2019).

Accurate assessments of both the current situation and opportunities for improvement require cost-effective approaches for evaluating on-farm yield and environmental footprint in relation to N inputs, thus enabling identification of fields with poor N use efficiency. For such an approach to be feasible, it would need to rely on a small number of parameters that are readily available from producers. To that end, we evaluated three metrics related to agronomic and environmental performance (hereby called ‘N-metrics’): partial factor productivity for N inputs from fertilizer and irrigation water (PFP_N), N balance, and yield-scaled N balance. The PFP_N – the ratio between grain yield and the amount of applied N inputs (Cassman et al., 1996) – represents an N fertilizer efficiency metric and only requires data on yield and N inputs. However, while PFP_N provides an indication of N fertilizer efficiency for grain production, it tells little about potential environmental impact and long-term sustainability of the resource base. It may also give a biased assessment of agronomic performance of the cropping system. For example, high PFP_N values can result from a combination of low yields and nil N inputs; if this situation continues over time, it would invariably lead to soil N mining, loss of soil quality, and, at scale, a deficient cereal supply. Another metric is the partial N balance (hereafter simply referred to as ‘N balance’), which is defined as the difference between N inputs and grain N removal (Treacy et al., 2008; Oenema et al., 2012; McLellan et al., 2018). As in the previous example, a persistent negative N balance over time would invariably lead to soil N mining. In contrast, a large N balance is a strong indicator of potentially large N losses. For example, in the case of maize, N losses increase exponentially when N balance exceeds 75 kg N ha^{-1} (Zhao et al., 2016; McLellan et al., 2018). An example of the application of the N balance approach is the framework for assessing N use or management developed by the European Union Nitrogen Expert Panel that considers (i) minimum amount of N input required for production; (ii) maximum N surplus that is environmentally acceptable; and (iii) minimum and maximum N use efficiency, defining a “safe operating space”, which shows the most desirable range for N output and N input (EU-NEP, 2015). Other examples of application of the N balance approach include whole-farm level assessments, including dairy farms (Schröder et al., 2003; Spears et al., 2003; Cela et al., 2014). Finally, N balance can also be expressed per unit of yield (hereafter referred to as ‘yield-scaled N balance’) to recognize the different land requirements associated with low- and high-yield cropping systems to meet a given production goal (Schröder et al., 2003; Grassini and Cassman, 2012). Estimating N balance and other N-metrics in producer fields can help understand potential N losses in current agro-ecosystems, on a per-area and per-output basis and, in the case of fields with large N balance and low PFP_N, identify opportunities for improvement *via* better crop and soil management practices (Cassman, 2017; McLellan et al., 2018).

To establish a baseline and determine the variability among maize fields in both production and environmental outcomes related to N input use, we developed an approach using producer-reported data, a combination of N-metrics (PFP_N, N balance, and yield-scaled N balance), and a spatial framework to cluster fields into near-similar climate-soil domains. We used Nebraska (NE), USA as a study case—a state that produces 43 MMT of maize annually in *ca.* 4 million ha (USDA-NASS, 2014–2018). The assessment was based on a large database including field-level data on yield and N fertilizer rates collected from irrigated and rainfed maize over multiple years (total of 9280 field-year observations). Specific objectives were to (i) determine current PFP_N, N balance, and yield-scaled N balance for irrigated and rainfed maize; (ii) evaluate the sensitivity of these N-metrics as a result of different levels of spatial and temporal aggregation (field averages, year averages, and individual field-year observations); and (iii) assess the influence of water regime and crop sequence on yield, N inputs, and N-metrics as a first step towards understanding how management practices affect these N performance metrics.

2. Materials and methods

2.1. Study region, on-farm database, and field grouping based on climate and soil

The United States accounts for 28% of global maize production (FAOSTAT, 2013-2017). About 90% of maize in the USA is produced in the north-central region, commonly referred to as the “Corn Belt”, where maize is grown as monoculture or in a 2-y rotation with soybean (Grassini et al., 2014). Nebraska ranks third among USA maize producing states, with irrigated area accounting for *ca.* 58% and 65% of total NE maize cropland and production, respectively (USDA-NASS, 2014–2018). Nebraska is divided into 23 Natural Resources Districts (NRDs; www.nrdnet.org), with each NRD serving as a government entity authorized to establish regulations to conserve water and soil resource quality and quantity (Exner et al., 2010; Ferguson, 2015). Some of the NRDs require producers with fields located within their boundaries to report field-level data on yield and applied inputs every year. In the present study, we used data reported from maize fields located in four NRDs: Little Blue, Lower Platte North, Tri-Basin, and Upper Big Blue (Fig. 1). Producer-reported data included field location (township, range, and section), maize yield (at standard moisture content of 155 g H_2O kg^{-1} grain), N fertilizer rate, irrigation amount, some management practices (previous crop, irrigation system type, and manure application), and NO_3^--N concentration contained in applied irrigation water. The database included irrigated and rainfed fields sown with maize during seven crop seasons (2009–2015) with contrasting weather conditions. For example, 2012 exhibited warmer and dry conditions, with seasonal temperature and total rainfall averaging 22°C and 202

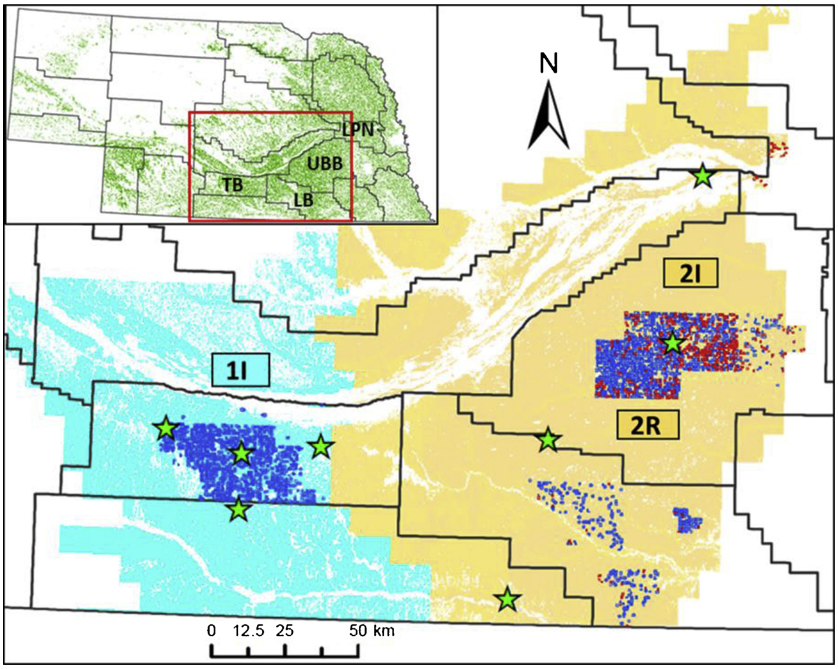

Fig. 1. Location of irrigated (blue dots; n = 8413 field-years) and rainfed maize fields (red dots; n = 867 field-years). Fields were grouped into two 'technology extrapolation domains' (TED 1 & 2) based on climate and soil similarity and fields in TED2 were further grouped based upon water regime (irrigated [2I] and rainfed [2R]), resulting in three TED-water regime combinations (TED 1I, 2I and 2R). Note that all fields in TED1 were irrigated. Stars indicate location of the meteorological stations. Inset shows maize harvested area (in green; USDA-NASS, 2017) and location of area of interest within Nebraska (NE). Lines show borders of NE Natural Resources Districts (NRDs). Producer data from four NRDs were used for the present study: Little Blue (LB), Lower Platte North (LPN), Tri Basin (TB), and Upper Big Blue (UBB). (For interpretation of the references to colour in this figure legend, the reader is referred to the webversion of this article.)

mm, respectively, across the study area. In contrast, 2014 was cooler and wet, with seasonal temperature and total rainfall averaging 20°C and 544 mm, respectively. Water table depth was consistently below the rooting depth across the region where the reporting fields were located.

Field boundaries were mapped using Google Earth® based on the field location as provided by the NRDs. Associated data were screened for erroneous and incomplete entries, using quality control measures that set acceptable ranges for yield, N inputs, and applied irrigation. For example, fields that reported maize yields > 20 Mg ha^{-1}, N fertilizer amounts > 350 kg N ha^{-1}, and/or applied irrigation > 1200 mm were excluded from the database (*ca.* 0.1% of total observations). Fields receiving manure application were excluded because (i) on average, only 5% of maize fields in NE receive manure (USDA-ERS, 2005), and (ii) it is difficult to estimate the release and amount of N from applied manure (van Kessel and Reeves, 2002). Only pivot-irrigated fields were considered for our study as surface (flood) irrigation accounts for a small fraction of irrigated maize area in NE (*ca.* 14%) and its area has steadily declined over time (USDA-ERS, 2010). Because the majority ($> 85\%$) of maize across the US Corn Belt region is grown continuously or in a maize-soybean rotation (Farmaha et al., 2016), fields sown with maize after wheat, alfalfa, or other crops besides maize and soybean were excluded from the analysis. Our study only included fields sown with maize for grain; other maize fields sown for seed production or silage were excluded. The group of reporting fields remained the same during the 2009–2015 time period in the four NRDs.

A robust comparison of producer fields in terms of yield, N inputs, and N-metrics requires grouping fields based on those factors with greatest influence on yield potential, yield stability and, indirectly, on nutrient cycling and other variables influencing crop responses to N inputs. In the present study, maize fields were grouped into technology extrapolation domains (TEDs; Rattalino Edreira et al., 2018). Briefly, a TED corresponds to a unique combination of annual growing-degree days (GDD), aridity index (ratio between precipitation and reference ET), temperature seasonality (as quantified with standard deviation for monthly temperature), and plant available water holding capacity (PAWHC). Within a defined region, such as the US Corn Belt, the TED framework categorizes soils into cohort groups, within which climate and soils are of sufficient similarity that crop responses to management practices (including N fertilizer) are expected to be similar. Detailed description of the TED spatial framework is available at http://www.yieldgap.org/web/guest/cz-ted. For our analysis, we grouped fields into two TEDs (TED 1 and 2) which, together, account for *ca.* 1.3 million ha land in the US sown with maize every year. Both TEDs have high temperature seasonality and same GDD range (*i.e.*, 3792–4829 °Cd). In contrast, TED 1 had higher PAWHC (300–350 *versus* 250 − 300 mm) and higher water limitation (*i.e.*, lower aridity index) compared to TED 2. The TED 1 only included irrigated fields, while TED 2 included both irrigated (I) and rainfed fields (R), which were disaggregated for the analysis. Hence, fields were grouped into three TED-water regime (TED-WR) combinations: TED 1I, TED 2I, TED 2R. After applying quality control measures and grouping the fields into the three TED-WRs, the database contained a total of 9280 field-year observations; of these, 91 and 9% corresponded to irrigated and rainfed fields, respectively. On average, there were 511, 691 and 124 fields per year in TEDs 1I, 2I, and 2R, respectively.

2.2. On-farm data quality assessment

Previous studies have found that NRD producer-reported data aligned well with data collected by other independent sources (Grassini et al., 2014). In this study, we further evaluated the quality of the NRD data by comparing average annual N fertilizer rates and yield derived from the NRD database against independent estimates from both producer survey data (Grassini et al., 2015; Gibson et al., 2019) and official statistics (USDA-NASS, http://quickstats.nass.usda.gov/; USDA-ERS, https://data.ers.usda.gov/) for each TED-WR. Survey data included two crop seasons (2010 and 2011) and a total of 48 field-years located within the same TED-WRs (1I, 2I, and 2R). For consistency, we used the 2010–2011 time period for all yield and fertilizer paired comparisons. Unfortunately, USDA ERS data on N fertilizer amount for irrigated and rainfed maize were aggregated at state level and only available for 2010; hence, the comparison between average N rate comparison against the NRD database was performed at different levels of spatial aggregation.

2.3. Retrieval of weather and soil data and simulation of yield potential for each TED-water regime in each year

Weather and soil data were retrieved to assess differences among selected TED-WR combinations. Averages of weather variables retrieved for each TED-year during the crop season (emergence to physiological maturity) were calculated for the 2009–2015 time period per TED. Average dates of emergence and physiological maturity in each year were simulated using Hybrid-Maize model (Yang et al., 2004, 2017) based on average sowing date and hybrid maturity data available for each TED-WR (Morell et al., 2016; Gibson et al., 2019) and measured daily weather data from three or four meteorological stations located within each TED (Fig. 1). Weather variables included incident solar radiation, minimum and maximum temperature (T_{min} and T_{max}, respectively), precipitation, and Penman-Monteith grass-referenced evapotranspiration (ET_o; Allen et al., 1998). Soil variables including percentage of soil organic matter, PAWHC, and topographic wetness index (TWI) for each field were retrieved from Soil Survey Geographic database (SSURGO, https://websoilsurvey.nrcs.usda.gov). PAWHC represents the amount of water (mm) that the soil can hold between field capacity and wilting point within the rootable depth. TWI indicates the likelihood of surface runoff (run-on) from (to) an area based on slope and surrounding area, with bottom and upland areas having highest and lowest values, respectively (Sørensen et al., 2006).

Yield potential (Yp) is defined as the yield attained by an adapted crop cultivar when grown with non-limiting nutrient and water supplies and with pests and diseases effectively controlled (Evans, 1993; van Ittersum et al., 2013). Water-limited yield potential (Yw) is influenced by the same factors that define Yp but also determined by precipitation amount and distribution and soil properties that influence water availability such as PAWHC and field slope. In our study, we estimated Yp and Yw for three purposes. First, the ratio between Yw and Yp provides an objective estimate of the degree of water limitation in rainfed *versus* irrigated fields in TED 2. Second, comparison of average producer yield against simulated Yp (irrigated fields) or Yw (rainfed fields) provides an estimate of the yield gap (difference between producer yield and Yp or Yw), which is useful to understand yield performance in relation to the N balance for a given field-year. For example, a large yield gap and a large N balance suggests an opportunity to produce more yield with the same or even smaller N balance. Third, expressing producer yield as a percentage of the Yp (or Yw) for a given TED-WR-year (hereafter referred to as 'relative yield') allows a fair comparison of producer yields and N balance across years with contrasting weather conditions, which is critical in the case of rainfed fields that depends on the erratic fluctuation in precipitation amount and distribution across years.

We used Hybrid-Maize model (Yang et al., 2006, 2017) to estimate Yp (irrigated) and Yw (rainfed) for each TED-WR-year combination. Hybrid-Maize model has been widely evaluated for its ability to estimate yield potential in well-managed crops that grew without nutrient limitations and kept free of biotic stresses (Yang et al., 2004; Grassini et al., 2009a). Because the goal was to estimate the maximum possible yield that results from the best possible management in each TED-WR, we selected the combination of sowing date, hybrid maturity, and plant density that give the highest yield in each TED-WR based on previous survey data (Farmaha et al., 2016; Gibson et al., 2019). Data inputs and model parameters used to simulate Yp or Yw are shown in Supplementary Tables S1-S2. Producer yield exceeded simulated Yp (or Yw) in 4% of the total field-year observations, likely due to inaccuracies in weather, soil, or producer yield data. For the purposes of this analysis, relative yield was set at one when producer yield exceeded Yp (or Yw).

2.4. Calculation of partial factor productivity for nitrogen (N) inputs, N balance, and yield-scaled N balance

The N inputs included N from synthetic fertilizer, applied irrigation water (in the case of pivot-irrigated fields), manure, atmospheric dry and wet deposition, inorganic soil N at sowing, and soil organic matter (SOM) mineralization during the crop season. Quantification of all N input sources for a large population of producer fields would require expensive and laborious measurements. Hence, we focused on those N inputs that account for the largest fraction of total N inputs and that are readily available from producer fields. In our study, we excluded fields receiving manure application as this is not a common practice in NE. In the case of atmospheric N deposition, NE is situated far from industrial areas and overall annual N deposition has been estimated to be very small (< 10 kg N ha^{-1}; NADP, USDA-REEIS, https://reeis.usda.gov/web/crisprojectpages/1007486-the-national-atmospheric-deposition-program-nadp.html). A key question is the relationship between N mineralization and immobilization, which may differ for a given field-year. However, given the stable stoichiometry between C and N, so long as SOM content does not change over time, the magnitude of these two processes would converge over the long-term. Because SOM is near steady state in the US Corn Belt (Baker and Griffith, 2005; Verma et al., 2005; Dolan et al., 2006; Blanco-Canqui and Lal, 2008), we assumed N released from SOM mineralization (which includes the inorganic soil N at sowing) to be similar to soil N immobilization over the full field-year. In contrast, the amount of N contained in applied irrigation water (hereafter referred to as "N irrigation") cannot be neglected for irrigated fields (Grassini et al., 2014; Ferguson, 2015). Hence, we considered N from both fertilizer and applied irrigation water for our calculation of PFP_N, N balance, and yield-scaled N balance.

Nitrogen added *via* irrigation was calculated from reported irrigation amount and NO_3^--N concentration in groundwater. For field-years with no data to estimate N irrigation (because irrigation amount and/or NO_3^--N concentration were not available), we used the average N irrigation calculated for other fields located within the same TED-WR-year. Because field-level irrigation amounts were not reported for TED 2I, we estimated a constant irrigation amount for all fields within a TED-year, using the relationship between seasonal water deficit and on-farm irrigation amount for silt loam soils reported by Gibson et al. (2018) for the same region. In the case of NO_3^--N concentration, we used the average value estimated across fields in TED2. We note that N irrigation accounts for a relatively small portion of the N inputs (*ca.* 11%), so the estimation of N irrigation for TED 2I is unlikely to bias results.

Partial factor productivity for N inputs (PFP_N) was calculated as the ratio between yield and N inputs. The N balance was calculated as the difference between N inputs and grain N removal. Maize grain N removal was estimated based on producer yield and grain nitrogen concentration (GNC, at standard 15.5% grain moisture content). The latter was estimated for each field-year using the predictive model developed by Tenorio et al. (2019) for maize in the US Corn Belt. We note that the goal is not to achieve zero N balance because that would lead to mining of soil organic matter. Instead, here we used a threshold of 75 kg N ha^{-1} to identify fields with large N balance and, hence, potentially large N losses (Zhao et al., 2016; McLellan et al., 2018). Using data from individual field-years may give a biased assessment of producer performace in relation with applied N inputs. For example, a severe drought (*e.g.,* year 2012) would reduce yield and lead to a relatively large N balance in rainfed fields. Likewise, a severe soil mining can be (wrongly) inferred from a field that (purposely) received little N fertilizer in an specific year because of large residual soil N from previous crop as measured using soil nitrate tests. To evaluate the degree to which our estimates of N balance may be biased due to the aforementioned factors, we calculated the N balance at three different levels of aggregation: (i) individual field-years, (ii) individual fields with N balance averaged across years, and (iii) individual years with N balance averaged across fields. In the case of (ii), we included only those fields with at least three years of data. Finally, the yield-scaled N balance was calculated as the ratio between N balance and producer yield.

Frequency distributions were used to assess variation in yield, N inputs, and N-metrics. Deviation from normality was tested using D'Agostino-Pearson normality test. In addition, a three-way analysis of variance (ANOVA) was used to quantify the influence of TED-WR, year, previous crop, and their interactions at explaining observed variation on yield, N inputs, N balance, PFP_N, and yield-scaled N balance. Proportion of sum of squares (%SS) attributable to each term was computed after excluding the error. Mean contrasts were used to assess the overall effect of water regime and crop sequence on the different parameters. Tukey's test was used to determine statistically significant differences among averages ($\alpha = 0.05$). To evaluate biases in the analysis due to data imbalance among TED-WRs, the ANOVA was repeated 5x using resampling of equally 300 observations in each TED-WR-previous crop combinations to obtain a balanced experimental design. The test indicated that using either a balanced *versus* unbalanced number of observations or different subsets of randomly selected fields had little impact on the results. Hence, we reported only the results derived from the ANOVA using the entire database. Yield *versus* N balance plots were assessed to determine the frequency of fields with small or large N balance and low or high yield. The analysis was also performed using relative yield (as % of Yp or Yw) to account for weather variation across years, TEDs, and WR. Fields were subsequently grouped in four categories: (A) high relative yield, N balance < 75 kg N ha^{-1}; (B) low relative yield, N balance < 75 kg N ha^{-1}; (C) high relative yield, N balance ≥ 75 kg N ha^{-1}; (D) low relative yield, N balance ≥ 75 kg N ha^{-1}. Following Lobell et al. (2009) and van Ittersum et al. (2013), we used 80% and 70% of Yp and Yw as thresholds to distinguish high *versus* low yields in irrigated and rainfed fields, respectively. These values represent reasonable yield goals, with the smaller yield goal in the case of rainfed crops aiming to account for higher production risk associated with erratic rainfall across years.

3. Results

3.1. On-farm yield, N inputs, and N-metrics across climate x soil x water regime domains

Averages of meteorological variables were similar between the three TED-WRs, except for ET_o, which tended to be higher in TED 1 *versus* TED 2 (Table 1). Maize fields exhibited higher PAWHC and TWI, and lower soil organic matter, in TED 1 compared with TED 2. Within TED 2, the slightly higher soil organic matter and TWI in irrigated fields compared with rainfed fields is likely related both to historical selection of the best soils for pivot irrigation installation and to greater crop residue return with higher-yield irrigated production. Weather and soil parameters exhibited relatively small year-to-year and field-to-field variation, respectively, as indicated by their respective coefficients of variation (CVs ≤ 16%); total precipitation was an important exception, exhibiting large variation across years in both TEDs (CVs = 30–35%) (Table 1).

Averages for NRD yield and N fertilizer were in reasonable agreement with estimates derived from independent survey data, collected from fields located in same NRD, with differences among databases within ± 4% of NRD averages and statistically not different from zero (*t*-test, $p > 0.10$) (Table 2). Similarly, there was good agreement between NRD and NASS maize yields as indicated by the lack of statistically significant difference between databases (*t*-test, $p > 0.15$). In contrast, average statewide N fertilizer data reported through NASS was 7–10% (irrigated) and 5% (rainfed) lower than average N fertilizer rate as reported to the NRDs (*t*-test, $p < 0.05$). Inclusion of other regions of NE with lower maize yields and, probably, lower fertilizer N amounts in the calculation of the statewide NASS average may explain these differences. Indeed, our study area has slightly higher average irrigated and rainfed maize yields (13.4 and 9.3 Mg ha^{-1}, respectively) compared with the state averages (12.7 and 9.0 Mg ha^{-1}; USDA-NASS, 2013–2017).

Table 2
Comparison for yield and N fertilizer among the Natural Resources District (NRD) database (this study), independent survey producer data (Grassini et al., 2015; Gibson et al., 2019), and official statistics (National Agricultural Statistics Service [USDA-NASS]; Economic Research Service [USDA-ERS]) for each technology extrapolation domain x water regime (TED-WR) combination. Values are 20102011 averages, except for average N fertilizer reported by ERS, which corresponds to an average statewide value reported for year 2010. Parenthetic values indicate the range. Note that a single aggregated value was available from USDA-NASS; hence, the range is not shown.

TED-WR	Yield (Mg ha^{-1})		
	NRD	Survey	NASS/ERS
1I	12.7 (6.3–17.6)	12.8 (10.7–15.0)	12.4
2I	12.5 (6.3–17.3)	13.0 (9.9–15.1)	12.0
2R	8.9 (1.9–13.8)	8.8 (6.4–9.7)	8.8
		N fertilizer rate (kg N ha^{-1})	
1I	210 (84–325)	218 (168–246)	189*
2I	204 (78–325)	215 (157–263)	
2R	138 (76–246)	144 (140–151)	131*

* Significantly different from mean NRD estimate (*t*-test, $\alpha = 0.05$).

Average producer yield represented *ca.* 81% of simulated Yp for irrigated fields and *ca.* 70% of Yw for rainfed crops (Table 3). Yield potential was 5% higher in TED 1I *versus* TED 2I due to longer crop cycle length (*i.e.*, days from emergence until physiological maturity) in the former as a result of lower seasonal temperature (Table 1). The Yw for rainfed maize in TED 2 was *ca.* 30% lower and three times more variable compared with the simulated Yp for irrigated maize in the same TED. Frequency distributions for producer yield in irrigated and rainfed fields were negatively skewed, with the majority of the fields closer to highest yields (Fig. 2a, c). TED-WR had the greatest influence on yield and N inputs, accounting for 70–90% of SS excluding the error, with the rest of the modelled variation mostly explained by year, TED-WR x year interaction, and, in the case of N inputs, also by previous crop (Table 4). This result was expected as the TED-WR stratification aimed to account for differences in climate, soil, and water supply between regions and water regimes. Average producer yield was *ca.* 40% lower (and 5x more variable) in rainfed *versus* irrigated fields (Table 3). Consistent with the yield difference, average N input was 44% higher in irrigated *versus* rainfed fields (Fig. 2b, d). In contrast to crop yield, the degree of inter-annual variation for N inputs was identical for both water regimes (CV = 6%). Distribution of field-level N inputs was

Table 1
Averages for weather and soil variables for each technology extrapolation domain x water regime (TED-WR) combination. Averages for weather variables during the 2009-2015 period were computed based on seasonal (emergence-to-physiological maturity) values, while averages for soil variables were computed based on the values retrieved for each individual field. Parenthetic values indicate inter-annual and field-to-field coefficient of variation (in %) for weather and soil variables, respectively. Different letters indicate statistically significant ($p < 0.05$, Tukey's test) differences among TED-WRs. Means of weather variables for irrigated and rainfed fields located in TED 2 were identical; hence, a single mean for each weather variable is shown for fields in TED 2.

TED	Water regime	Solar radiation (MJ $m^{-2}d^{-1}$)	Tmin (ºC)	Tmax (ºC)	Total ETo (mm)	Total rainfall (mm)	Soil organic matter (%)	PAWHC (mm)	TWI
1	Irrigated	20.9 (7)^a	13.0 (6)^a	27.0 (6)^a	720 (5)^a	371 (35)^a	1.9 (10)^c	313 (3)^a	10.3 (4)^a
2	Irrigated	20.9 (6)^a	14.1 (7)^a	27.6 (5)^a	673 (5)^b	393 (31)^a	2.5 (13)^a	285 (3)^b	10.1 (6)^b
	Rainfed						2.4 (16)^b	287 (3)^b	9.9 (6)^c

Tmin: minimum temperature; Tmax: maximum temperature; ET_o: grass-based reference evapotranspiration; PAWHC: plant available water holding capacity; TWI: topographic wetness index.

Table 3
Average 7-y (2009- 2015) producer yield, yield potential (Yp; irrigated crops) or water-limited yield potential (Yw; rainfed crops), and relative yield (ratio between producer yield and Yp or Yw) for each technology extrapolation domain x water regime (TED-WR) combination. Parenthetic values indicate the inter-annual coefficient of variation (in %).

TED-WR	Producer yield (Mg ha^{-1})	Yp or Yw (Mg ha^{-1})	Relative yield
1I	13.9 (8)^{a}	17.1 (7)^{a}	0.81 (11)^{a}
2I	13.3 (4)^{b}	16.6 (10)^{b}	0.80 (9)^{b}
2R	8.2 (28)^{c}	11.8 (31)^{c}	0.69 (13)^{c}

Different letters indicate statistically significant differences among TED-WRs ($p < 0.05$, Tukey's test).

normally distributed in irrigated fields but positively skewed in rainfed fields, indicating that a relatively smaller number of fields received much larger N inputs than the rest of the fields. In irrigated fields, N fertilizer exhibited a negatively skewed distribution (skewness = -0.19). Average N irrigation represented 11% of the N input in irrigated fields, exhibiting larger inter-annual variation compared with N fertilizer (CV = 41 *versus* 4%) as a result of variation in irrigation amounts across years in response to water demand as affected by weather (Fig. 2b, inset).

Frequency distribution for N balance and PFP$_N$ showed contrasting patterns between water regimes: the N balance was negatively and positively skewed in irrigated and rainfed fields, respectively (Fig. 3a, d) while PFP$_N$ exhibited the inverse trend (Fig. 3b, e). However, yield-

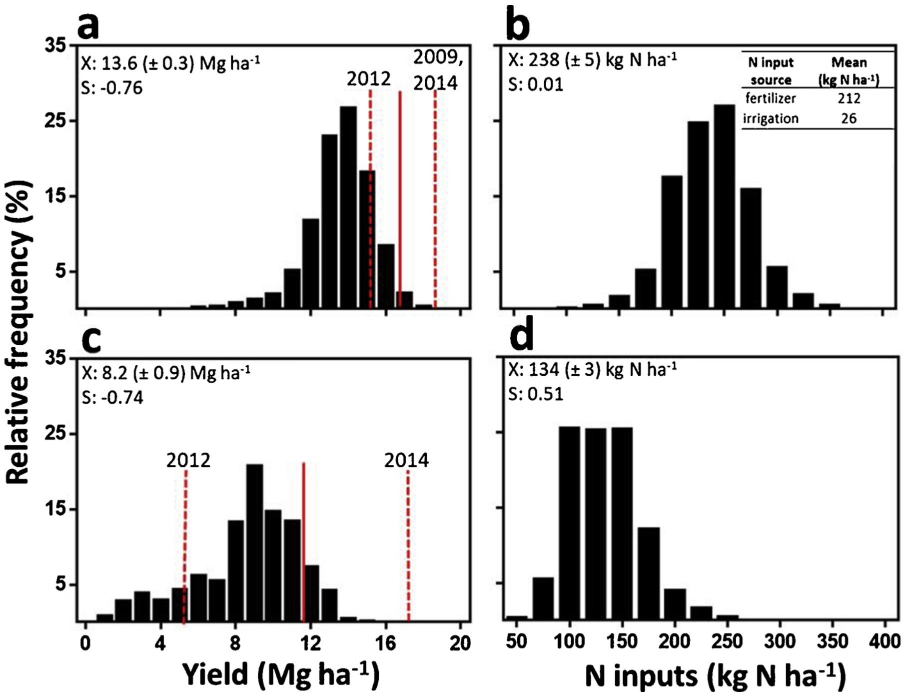

Fig. 2. Frequency distributions for producer yield (left) and N inputs (right) in irrigated (a, b); and rainfed fields (c, d). Number of field-years were 8413 (irrigated) and 867 (rainfed). Average (solid line), maximum and minimum (dashed lines) annual simulated yield potential (irrigated) or water-limited yield potential (rainfed) are shown. Inset in panel b shows averages for N fertilizer and N irrigation. Average (X ± standard error) and skewness (S) are shown. Irrigated data from technology extrapolation domains (TEDs) 1 and 2 were pooled as frequency distributions for yield and N inputs were almost identical.

Table 4
Analysis of variance for the effect of technology extrapolation domain x water regime combination (TED-WR), year, previous crop, and their interactions on yield, nitrogen (N) inputs, N balance, partial factor productivity for N inputs (PFP$_N$), and yield-scaled N balance. Mean difference of each parameter for soybean-maize *versus* continuous maize and irrigated *versus* rainfed fields in TED2 are shown.

			Percentage of total sum of squares (%SS)[†]			
Source of variation	d.f.	Yield [‡] (Mg ha^{-1})	N inputs [‡] (kg N ha^{-1})	N balance [‡] (kg N ha^{-1})	PFP$_N$ [‡] (kg grain kg^{-1} N)	N balance per yield unit[‡] (kg N Mg^{-1} grain)
TED-WR	2	72***	87***	49***	5***	7***
Year	6	14***	3***	16***	48***	41***
Previous crop	1	< 1***	5***	23***	17***	5***
TED-WR x year	12	13***	4***	9***	26***	39***
TED-WR x previous crop	2	< 1***	< 1***	1***	< 1	< 1**
Year x previous crop	6	< 1***	< 1	< 1*	1***	3***
TED-WR x year x previous crop	12	< 1***	< 1*	1***	2***	4***
Mean estimate difference						
previous crop (soybean *vs* maize)		0.2***	−20***	−22***	7***	−2***
water regime (irrigated *vs* rainfed in TED 2)		5***	96***	35***	−4***	−3***
Model sum of squares	41	27900	8825481	2662321	366282	85024
Error sum of squares	9238	21821	8731687	9219978	1078117	155610

[†] Proportion (in %) of total sum of squares (SS) after excluding error.

[‡] F-test significant at $P < 0.05$*, < 0.01**, and < 0.001***.

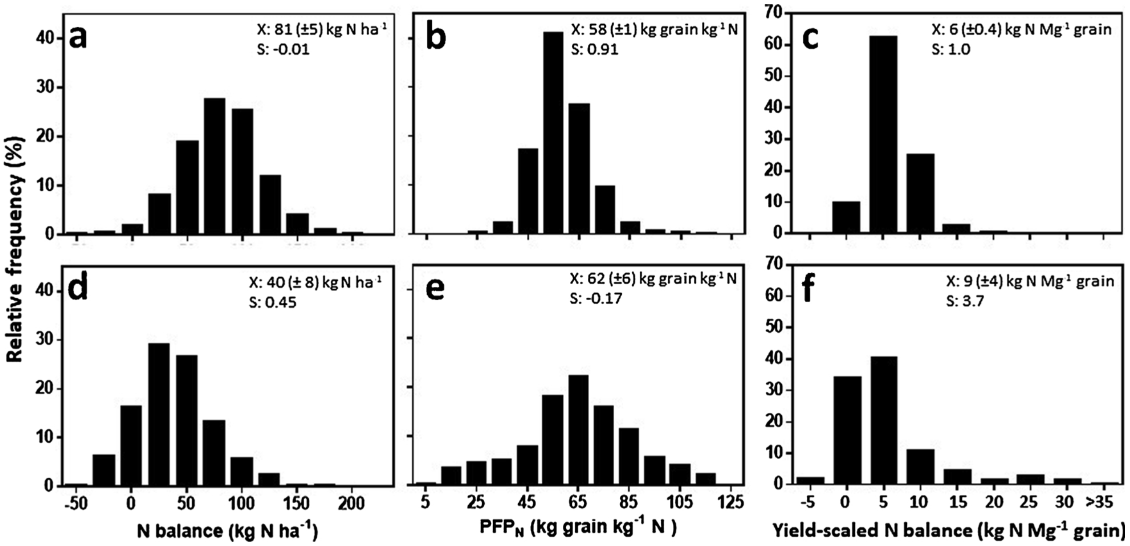

Fig. 3. Frequency distributions for nitrogen (N) balance (left), partial factor productivity for N inputs (PFP$_N$, center), and yield-scaled N balance (right) in irrigated (a, b, c) and rainfed fields (d, e, f). Number of field-years were 8413 (irrigated) and 867 (rainfed). Average (X ± standard error) and skewness (S) are shown. Irrigated data from technology extrapolation domains (TEDs) 1 and 2 were pooled as frequency distributions for yield and N inputs were almost identical.

scaled N balance was positively skewed in both water regimes (Fig. 3c, f), indicating that a relatively small number of fields in irrigated (1%) and rainfed (9%) exhibited very large yield-scaled N balance ($>$ 15 kg N Mg^{-1} grain).

The TED-WR term of our ANOVA explained *ca.* half of the modelled variation in N balance; the rest of the variation was accounted for by year, TED-WR x year, and previous crop (Table 4). In contrast, TED-WR explained a small portion of modelled variation in PFP$_N$ and yield-scaled N balance ($<$ 10%), with most variation accounted for by year, TED-WR x year, and, in the case of PFP$_N$, by previous crop as well. The large portion of unaccounted variation in N balance, PFP$_N$, and yield-scaled N balance (78, 75, and 65% of total SS, respectively) suggests that magnitude of field-to-field variation was as important as variation due to TED-WR, year, previous crops, and their interactions.

3.2. Benchmarking yield and N balance in producer fields

Similar to the observed pattern in average yield, the average N balance, calculated using all field-year observations, decreased in the following order: TED 1I (86 kg N ha^{-1}), 2I (77 kg N ha^{-1}) and 2R (38 kg N ha^{-1}) (Fig. 4a–c). About 61, 54, and 15% of the field-years in TED 1I, 2I, and 2R, respectively, exhibited N balance $\geq$ 75 kg N ha^{-1}. Results were similar when field averages (*i.e.*, averages for each field based on at least 3 years of data) were used for the analysis instead of individual field-year observations (Fig. 4d–f), except that the range of N balance narrowed considerably. For example, cases with very large N balance ($>$ 150 kg N ha^{-1}) or negative N balance were not apparent when the analysis was based on field averages instead of field-years.

Average annual N balance did not vary substantially among years in the case of irrigated maize (CV = 10%) (Fig. 4g, h). In contrast, rainfed maize exhibited a large year-to-year variation (CV = 46%), with larger (smaller) N balance corresponded to years with lower (higher) yield (Fig. 4i). For instance, highest N balance in TED 2R (rainfed) occurred in 2012, which corresponded to a drought year with very low yield. The year-to-year variation in N balance in irrigated fields was mostly due to variation in N irrigation (CV = 34–56%), but not in N fertilizer (CV = 3–5%).

Analysis of yield variation across field-years, for a given N balance level, is confounded by year-to-year variation in weather. Expressing producer yields as percentage of Yp (irrigated fields) or Yw (rainfed fields) using field averages allows an objective assessment of available room for improving yield at a given N balance level through better agronomic practices. About 41 and 52% of the irrigated and rainfed fields fell into the low relative yield categories (*i.e.,* below 80% and 70% of Yp and Yw, respectively, categories B and D in Fig. 5), indicating room to further increase yields within the observed range of N balance (Fig. 5). Of particular concern are those fields exhibiting large N balance *and* low relative yield (category D), representing 29 and 3% of total irrigated and rainfed fields, respectively. Attaining high yields with a smaller N balance (category A) is a realistic goal: 26% and 47% of irrigated and rainfed fields, respectively, exhibited N balance $<$ 75 kg N ha^{-1} *and* attained or even exceeded their respective yield goals.

3.3. Yield, N inputs and N-metrics as influenced by TED, water regime, and previous crop

Average N input rates were 44% larger in irrigated *versus* rainfed fields, but higher yields in irrigated fields meant that PFP$_N$ was remarkably similar between water regimes (Table 4, Fig. 3). And while N balance was 49% larger in irrigated *versus* rainfed fields, yield-scaled N balance was smaller in irrigated fields. For a given TED-WR, yield and N inputs were 2% lower and 10% larger, respectively, in maize after maize *versus* maize after soybean (Table 4, Fig. 6). As a result, PFP$_N$ and N balance was higher and lower, respectively, in maize after soybean compared to maize after maize. Consistent with these results, frequency of fields with N balance $\geq$ 75 kg N ha^{-1} was lower in soybean-maize than in maize-maize: 40% *versus* 72% (irrigated fields) and 13% *versus* 20% (rainfed fields).

4. Discussion

Benchmarking crop yields against external input use provides insight about opportunities to increase producer profit while using the same or less amount of input. There are many examples using this approach in the literature. For example, in a classic study, French and Schultz (1984) developed a boundary function for the relationship between yield and seasonal water supply for wheat in Australia; these authors documented large variation in yield across a wide range of water supply, which was attributable to management. This framework has been subsequently used in a multitude of studies to assess crop water productivity and identify opportunities for improvement (Sadras and Angus, 2006; Passioura, 2006; Grassini et al., 2009b, 2011). As far as we know, Hochman et al. (2014) is the only study that used a similar approach to benchmark crop yields in relation with N inputs. These

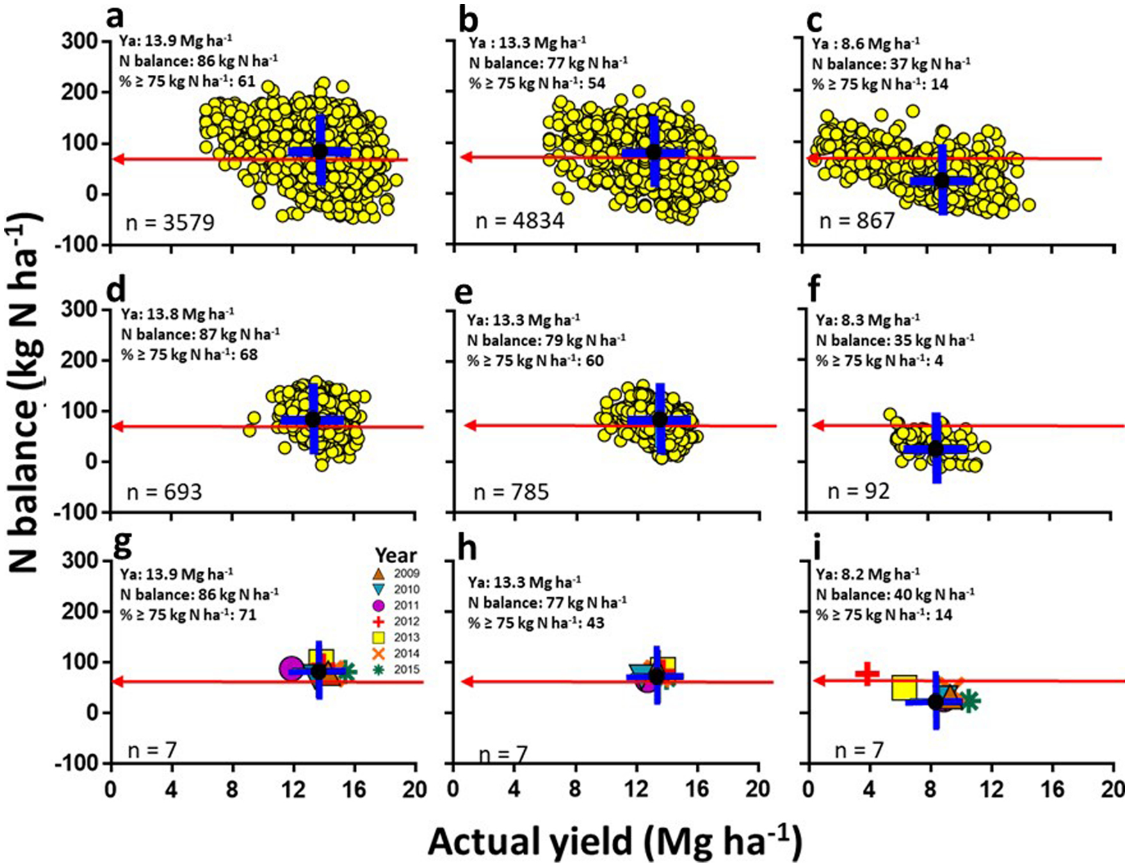

Fig. 4. Nitrogen (N) balance and producer maize yield in irrigated fields in TED 1 (1I; left) and TED 2 (2I; center) and rainfed fields in TED 2 (2R; right). Each datapoint represents a field-year observation (a, b, c), field averages based on 3 years of data or more (d, e, f), and annual averages based on all fields in a given year (g, h, i). Horizontal arrows indicate N balance $= 75$ kg N ha^{-1}, which was used as a threshold to identify fields with large N balance. Average yield (Ya) and N balance are shown (and indicated with blue crosses). Percentage of field-years (a, b, c), field averages (d, e, f), and years (g, h, i) with N balance $\geq$ 75 kg N ha^{-1} is also shown. n = number of observations.

authors presented an input-yield production frontier that benchmarked the efficiency of applied N fertilizer in terms of crop production; however, the approach had a (data-intensive) modeling component to estimate crop N requirement and did not explicitly focus on assessing potential N losses or estimating the N balance. In contrast, our study provides a cost-effective approach to benchmark yields in relation to N balance of individual producer fields using several readily-available parameters.

At issue is the degree to which the observed variation in N balance across producer fields is attributable to variation in agronomic management. Our study showed that field-to-field variation in N balance was much larger than the portion of variance accounted for by year, TED-WR, crop sequence, and their interactions (*ca.* 75 *versus* 25%, respectively; Table 4). Similarly, although fields were grouped into TED-WRs, and N balance was averaged across years, there was still large variation in N balance at any given yield level and *vice versa*. For instance, at a yield level of *ca*. 13 Mg ha^{-1}, the N balance in irrigated fields varied from 20 to 150 kg N ha^{-1} (Fig. 4). While some of this variation can be attributed to remaining spatial and temporal variation in climate and soil within each TED-WR combination, these findings suggest that management practices likely have a large influence on on-farm N balance. It is still uncertain, however, how much of that variation is manageable through cost-effective agronomic technologies. In this regard, a key challenge to improved N fertilizer efficiency is that

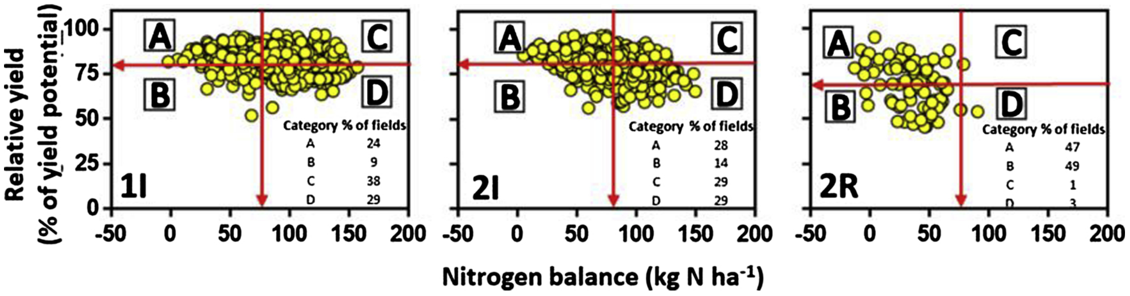

Fig. 5. Relative yield and nitrogen (N) balance in irrigated fields in TED 1 (1I; left) and TED 2 (2I; center) and rainfed fields in TED 2 (2R; right). Relative yield was calculated based on producer yield expressed as percentage of yield potential (Yp; irrigated) or water-limited yield potential (Yw; rainfed). Each datapoint represents a field average based on at least 3 years of data. Vertical line indicates N balance $=$ 75 kg N ha^{-1}, which was used as a threshold to identify fields with small and large N balance. Horizontal lines indicate 80% and 70% of Yp and Yw, which are reasonable yield goals for irrigated and rainfed fields, respectively. Frequency of fields in each of four (yield x N balance categories) combinations are shown.

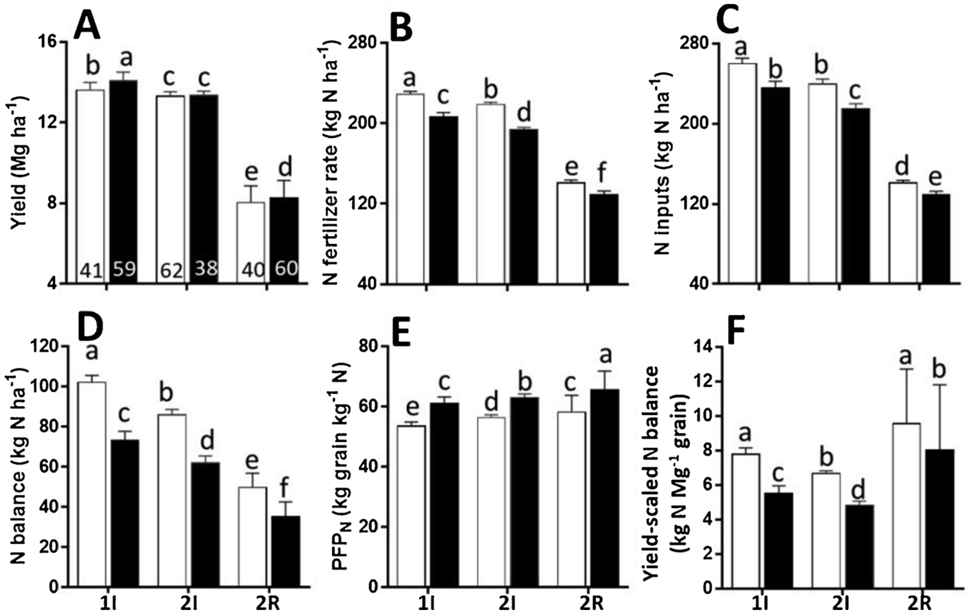

Fig. 6. Average producer yield, nitrogen (N) fertilizer rate, N inputs, N balance, partial factor productivity for N inputs (PFP$_N$), and yield-scaled N balance in the three technology extrapolation domain-water regime (TED-WR) combinations: irrigated TED 1(1I), irrigated TED 2 (2I), and rainfed TED 2 (2R). Separate averages are shown for fields sown with maize after maize (empty bars) or after soybean (solid bars). Averages were calculated based on annual averages, with vertical lines indicating the standard errors. Different letters indicate statistically significant differences among TED-WR x previous crop combinations (Tukey's test; $p < 0.05$). Percentage of fields sown with maize after maize or soybean in each TED-WR combination is shown in (A).

producers apply fertilizer without knowing the magnitude of total crop N demand, which is largely determined by Yp (or Yw in the case of rainfed fields) of the crop season ahead. If the season is unfavorable, the amount of N fertilizer they apply may be too large compared with crop N requirements that year. In contrast, if the year has Yp (or Yw) well above average, the applied N fertilizer may be insufficient to meet crop N requirements. Uncertainty in yield and N demand is most important in rainfed fields because Yw fluctuates dramatically from year to year (inter-annual CV = 31%) as a result of contrasting in-season precipitation amounts and temporal distribution, while N fertilizer remains fairly constant (inter-annual CV = 6%) as rainfed producers did not try to adjust N fertilizer rates in response to the large annual yield variation. Not surprisingly, our study showed that N balance was smaller and more variable in rainfed *versus* irrigated fields as a result of its higher climatic risk (Fig. 4). We note that NE is a harsh environment for rainfed maize production; in contrast, irrigated maize yield (and its stability) in NE are comparable to those of rainfed maize production in the most favorable environments in the eastern and central portions of the US Corn Belt (Grassini et al., 2014). Hence, results from this study for irrigated maize in NE are likely to be comparable to those for maize grown in favorable rainfed environments in the US Corn Belt.

While it may be difficult for producers to optimize N balance based on in-season weather, there may be other options that can help reduce the N balance regardless of the year-specific weather, and with little (if nil) yield penalty. Irrigated maize in rotation with soybean received smaller N fertilizer amounts and achieved higher yields, which is consistent with previous findings (Grassini et al., 2011; Farmaha et al., 2016), leading to substantially smaller N balance (Fig. 6). In connection to this finding, we note that future studies addressing the N balance in agro-ecosystems should aim to include the entire crop sequence into the analysis rather than individual crops. This is critical in the case of maize-soybean rotation considering the typical negative N balance during the soybean cycle, as a result of large seed N removal without addition of N fertilizer, as documented by a number of studies (Connor et al., 2011; Santachiara et al., 2017; Ciampitti and Salvagiotti, 2018). While the goal of having N balance < 75 kg N ha^{-1} seems realistic for continuous maize systems, this threshold may need to be re-examined in the case of maize-soybean sequences where an apparent large N balance during the maize cycle may actually be needed if the goal is to keep the N balance for the entire crop sequence above a level at which there is sufficient N to maintain soil organic matter at steady state.

Our proposed framework to categorize fields into low/small N balance and yield gap is useful to inform meaningful agronomic interventions and orient policy (Fig. 5). Firstly, our findings demonstrated that the goal of achieving high yields without a large N balance is not an oxymoron as 25% of the fields in our study cases achieved these two goals simultaneously (category A in Fig. 5). Secondly, the framework can help avoid the "one-size-fits-all" solutions promoted by some environmental advocacy groups that propose restricting the amount of N fertilizer that can be applied across all fields regardless of crop yields and N demand. This approach would punish producers who are already producing high yields while achieving small positive N balance. Instead, agronomic and extension efforts should focus on those fields with large positive N balance and large yield gaps (category D in Fig. 5), which roughly represent 30% of the irrigated fields in our study and likely contributed disproportionately more to the overall N footprint compared with the other fields. Similar findings have been reported for irrigated wheat in Mexico (Ahrens et al., 2010). Finally, the framework is useful for individual producer and crop consultants to diagnose their current N fertilizer management, serving as a starting point to identify inefficiencies and possible solutions. For example, if the current yield gap is small, it may be wise for producers to look for opportunities to reduce N input use without reducing crop yields, which would lead to greater input-use efficiency and extra producer revenue as it has been documented in the case of irrigation water management in NE (Irmak et al., 2012; Gibson et al., 2019).

Our assessment makes two key contributions relative to estimation of N balance. First, our study showed that calculation of N balance for individual fields should rely on more than one year to avoid the confounding effect of weather and episodic adjustments in N fertilizer rates to account for large residual soil N from previous crop or other factors. For example, the analysis based on all field-year observations would have pointed out to an important number of fields with apparent soil mining (*i.e.,* negative N balance) or very large N balance; this pattern was not apparent when the analysis was based on average N balance using three or more years (Fig. 4). Second, our assessment clearly indicated that using a suite of N-metrics is more robust compared with the use of single indicators. For instance, results in this study showed that (low-input) rainfed systems exhibited lower N balance with almost same PFP$_N$ compared to (high-input) irrigated systems. However, in a broader scale, to reach the same total grain production target, the low-input system would need *ca.* 40% more cropland, which would lead to an overall N balance (on a regional basis) that is similar or even higher compared with the high-input irrigated systems. In other words, as reported by previous studies (*e.g.,* Grassini and Cassman, 2012), when the N balance was scaled by yield (*i.e.,* yield-scaled N balance), the apparent advantage of low-input *versus* high-input systems vanished. So, while N balance at a field-level would be the proper indicator to evaluate environmental footprint in relation to crop-system performance, yield-scaled N balance is a more relevant metric for regional and global assessments that account for possible changes in land use for agricultural production to meet future food demand.

5. Conclusions

We followed an approach that consists of producer field-level data, a suite of N-metrics and a spatial framework to diagnose N input use in relation to crop yield and environmental outcomes in rainfed and irrigated maize fields in the western US Corn Belt. Our study indicated that there is substantial room to improve yield and/or reduce N balance through agronomic management (*e.g.,* crop rotation instead of continuous maize). Achieving high yields with relatively small positive N balance are not conflicting goals and *ca.* 25% of the producers are already reaching these goals simultaneously. Although NE was used as a case study for proof of concept, the approach can be extended to other cereal-based systems around the world. This study demonstrated the value of a comprehensive and confidential field-level producer data in providing useful information to producers, supply-chain companies, and policy makers in improving yield and reducing N losses from agricultural production.

Declaration of Competing Interest

The authors declare that there are no conflicts of interest.

Acknowledgements

Financial support was received from the Nebraska Corn Board (NCB), the Environmental Defense Fund (EDF), and the Agriculture and Food Research Initiative (AFRI) of the United States Department of Agriculture (USDA), Grant # 12431808. We are grateful to staff, boards, and producers of the Little Blue, Lower Platte North, Tri-Basin, and Upper Big Blue Natural Resources Districts (NRDs) for providing access to the producer data. We also thank Drs. Trenton Franz, Juan Ignacio Rattalino Edreira, and Haishun Yang for providing useful comments.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agee.2020.106865.

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