Yield gaps, the difference between potential yield and farmer yield, provide an estimate of the yield improvement possible without any change in potential yield (Cassman et al., 2003; Lobell et al., 2009). Large YGs imply that there is more potential for yield improvement. Evans (1993, p. 292) and Evans and Fischer (1999) defined potential yield as “the yield of a cultivar when grown in environments to which it is adapted; with nutrients and water not limiting; and with pests, diseases, weeds, lodging, and other stresses effectively controlled”. Potential yield represents the ability of a crop to convert solar radiation to dry matter and economic yield in a specific environment in the absence of stress.

The practical definition of potential yield may not be as simple as implied by Evans (1993, p. 292) and Evans and Fischer (1999). Potential yield is location specific making it necessary to aggregate local estimates spatially and temporally to produce average estimates for larger areas (van Ittersum et al., 2013). Cultural practices (cultivar, planting date, plant population, etc.) affect yield making it necessary to specify the use of best management practices when defining potential yield (Loomis and Connor, 1992, p. 10; van Ittersum et al., 2013). It is not yet clear if potential yield depends on soil type or if the elimination of water and nutrient stress decouples potential yield from soil characteristics (van Ittersum et al., 2013; Egli and Hatfield, 2014). Loomis and Connor (1992, p. 10) and Lobell et al. (2009) introduced the concept of water limited potential yield (i.e., potential yield in rain-fed environments) which may be more relevant when irrigation is not an option. Water limited potential yield would clearly be affected by soil characteristics.

Estimates of potential yield can be obtained from record farmer yields (i.e., winners of yield contests), maximum farmer yields, yields from well-managed agricultural experiment station experiments, or estimates from well-validated crop simulation models (Lobell et al., 2009). Global estimates are sometimes based on maximum farmer yield in a specific climate zone (Licker et al., 2010), but such estimates may not account for the variation in climate conditions or cropping systems at smaller scales (van Ittersum et al., 2013).

Yield gaps for corn, summarized by Lobell et al. (2009), ranged from 44 (YG as a percent of potential yield) to 84% with large YGs often associated with low farm yields. van Wart’s et al. (2013) estimates of national corn yield gaps in the United States (data from 1986–2008) ranged from 26% (rain fed) to 22% (irrigated) of potential yield. Site-specific YGs for individual corn fields varied substantially in western Kenya (water limited potential yield), but were much less variable among irrigated fields in Nebraska. The average YG in western
Kenya was 68% of the water limited potential yield compared with only 11% of the potential yield in Nebraska (van Ittersum et al., 2013).

Lobell et al. (2009) concluded that YGs for wheat (Triticum spp.) and rice (Oryza sativa L.) from major cropping systems of the world varied from 20 to 80% of the potential yield at most locations. Larger YGs were often found in low technology systems in comparison to high-technology irrigated systems. Licker et al. (2010) reported similar variation on a global scale and their estimates sometimes followed political boundaries, apparently reflecting the effect of the political system on the availability of technology.

The YG for a given location will depend on the farmer yield (high or low-input production system) and the method used to estimate potential yield (Liang et al., 2011; Meng et al., 2013). Lobell et al. (2009) suggested that, for a specific farm yield, the YG will probably be largest for modeled potential yield, followed by experiment yields and finally by maximum farmer yield. The plethora of potential yield estimates complicates evaluation of the variation in YGs and devising remedial strategies. The larger the geographical scale of the estimates of potential and farmer yield, the more difficult it is to evaluate the possibilities of reducing the YG (van Ittersum et al., 2013).

Our previous evaluation of soybean \(\text{Glycine max} (L.)\) Merr. YGs focused on production systems with variable farmer yields (Kentucky, Iowa, and Nebraska–Irrigated), but only minor differences in the availability of technology, the economic climate and skills of the producers (Egli and Hatfield, 2014). Our objective in that study, which was based on county yield data from 1972 to 2011, was to evaluate the magnitude, temporal trends, and the fundamental basis of the difference between the APY and county yield (i.e., YG). This manuscript reports the extension of that work to corn, a somewhat dissimilar crop that produces higher yield and generally requires more intense management (Egli, 2008a), using the same counties and techniques used with soybean (Egli and Hatfield, 2014).

**MATERIALS AND METHODS**

County corn yield estimates from 1972 through 2011 were obtained from the National Agricultural Statistics Service website (http://www.nass.usda.gov/, accessed 2 July 2014). Three states—Kentucky, Iowa, and Nebraska were selected to provide a range in productivity in close geographic proximity and with similar access to production technology. Only irrigated production in Nebraska was included to provide a relatively low-stress high-yield environment. Counties with less than roughly 4048 harvested hectares (10,000 acres) in 2011 were excluded from the analysis to avoid introducing possible artifacts resulting from small production areas. Thirty-two counties in Kentucky and 36 in Nebraska met the criterion. All 99 counties in Iowa exceeded the minimum harvested area, so 47 were chosen at random to create a manageable data set. In Kentucky, 10 of the 32 counties had less than 4048 harvested hectares in 1972, but by 1976 only two counties were less than the minimum. All 47 Iowa counties exceeded the minimum harvested area in 1972. Three counties in Nebraska had less than 4048 irrigated ha in 1972, but by 1977 all counties exceeded the minimum harvested area. The counties included in this analysis were essentially the same counties used previously in an evaluation of soybean yield trends (Egli, 2008b) and soybean YGs (Egli and Hatfield, 2014).

A quantile regression analysis set at the 95th percentile \(\text{PROC QUANTREG in SAS (SAS for Windows, v. 9.3, SAS Institute, Cary, NC)}\) (Webb, 1972; Cade and Noon, 2003) was used to estimate yield in the most favorable environments that occurred in each county from 1972 to 2011. This estimate represents the aggregate accomplishment of all of the farmers in each county in favorable conditions so it is similar to the maximum farmer yield estimate of potential yield described by Lobell et al. (2009).

The YG (g m\(^{-2}\)) was calculated by subtracting the county yield for each year from the APY for that year calculated from the quantile regression equation as described previously (Egli and Hatfield, 2014). The RYG was calculated by dividing the absolute YG by APY and multiplying by 100.

The national commodity crop productivity index (NCCPI) for each county was obtained through use of gSUSURGO data and NCCPI values by soil map unit using the 2013 gSUSURO data for the conterminous United States which were resampled and mosaiced to create a national soils raster at 100 m resolution (Soil Survey Staff, 2012). The national soils raster attribute table was joined with the NCCPI values by soil map unit (Soil Survey Staff, 2013). Mean NCCPI values were calculated for all soils within a county using ArcGIS: ZonalStatisticsAsTable, for each of the selected counties in Kentucky, Iowa, and Nebraska (ESRI 2012. ArcGIS Desktop: Release 10.1, sp1. Redlands, CA:Esri.). To constrain the NCCPI values only to agricultural land within each county, mean NCCPI values were calculated using a mask of specified land use classes from the 2009 NASS Cropland Data Layer (NASS, 2009) combined with ArcGIS: ZonalStatisticsAsTable for (agricultural land/row crop agriculture) in each of the selected counties in the three states (ESRI 2012. ArcGIS Desktop Release 10.1, sp1. Redlands, CA:Esri.).

The statistical package in Sigma Plot (Sigma Plot 12.0, SSPS Inc., Chicago, IL) was used for all regression analysis.
RESULTS

The results of the quantile regression analysis for the highest and lowest yielding counties in the 115 counties evaluated are illustrated in Fig. 1. The average county yield (1972–2011) in Phelps County, Nebraska, was 1001 g m⁻² compared with 579 g m⁻² for Marshall County, Kentucky. The APY increased with time in all 115 counties (data not shown), in step with the general trend for increasing county yields. There was a substantial range in the rate of increase of APY among counties with the maximum rate (16.8 g m⁻² yr⁻¹, Cuming County, Nebraska) 2.7 times the minimum rate (6.3 g m⁻² yr⁻¹, Calhoun County, Kentucky), but only Iowa showed a significant association between rate of growth in APY and average county yield ($r = 0.41^*$, $n = 47$).

Nebraska (Irrigated) had the highest mean county yield and Kentucky the lowest (26% less than Nebraska), with Iowa intermediate between the extremes (Table 1). There was, however, substantial overlap among the three states. There was nearly a twofold difference in average yield (579–1001 g m⁻²) among the 115 counties. The mean APY in Kentucky was 20% less than Nebraska (irrigated). The mean APY was closely associated with mean county yields ($r = 0.85^{**}$, 0.90** and 0.83** for Kentucky, Iowa, and Nebraska, respectively) as expected given the method of estimating APY.

The mean RYG was smallest in Nebraska (9–16%) and there was considerable overlap between Kentucky (14–24%) and Iowa (11–26%) (Fig 2). The mean RYG decreased significantly ($p < 0.10$) within each state as the mean county yield increased so the largest RYGs occurred in the less-productive counties.

Table 1. Corn production statistics for Kentucky, Iowa, and Nebraska (irrigated). Mean yield (1972–2011).

<table>
<thead>
<tr>
<th>State</th>
<th>No. of counties</th>
<th>County yield</th>
<th>Attainable potential yield</th>
<th>Coefficient of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kentucky</td>
<td>32</td>
<td>680</td>
<td>786–579</td>
<td>837</td>
</tr>
<tr>
<td>Iowa</td>
<td>47</td>
<td>810</td>
<td>887–662</td>
<td>968</td>
</tr>
<tr>
<td>Nebraska–irrigated</td>
<td>36</td>
<td>919</td>
<td>1001–868</td>
<td>1040</td>
</tr>
</tbody>
</table>

There was substantial variation of the mean RYG with time for the four highest- and the four-lowest-yielding counties in each state (Fig. 3). The average RYG for the high-yield counties (roughly 15% in Kentucky and Iowa and 9% in Nebraska) was smaller than in the lowest-yielding counties (roughly 21% in Kentucky and Iowa and 14% in Nebraska). The largest RYGs were more than 50% in Kentucky and Iowa, but they never exceeded 40% in Nebraska. Large and small RYGs usually occurred in the same year in both high- and low-county yields. The year-to-year variation was substantially less in the low-stress irrigated environment in Nebraska (Fig. 3C).

There was no obvious temporal trend of RYG in Kentucky where linear regression of RYG vs. time identified a significant ($p < 0.10$) relationship in only 5 of 32 counties (two with a positive slope and three with a negative slope). Linear regression was significant ($p < 0.10$) in 10 of 47 counties in Iowa (all with a negative slope) and 16 of 36 counties in Nebraska (all with a negative slope).
Mean country yield in Kentucky and Iowa was associated with the national commodity crop productivity index-agriculture (NCCPI-AG) (linear regression was significant at \( p < 0.0001, r^2 = 0.58 \) (Fig. 4). There was very little overlap between the two states, but there was substantial variation in mean yield that was not accounted for by the NCCPI-AG. The NCCPI-AG was designed for non-irrigated production (NRCS, 2008), so we did not relate it to yield in Nebraska.

**DISCUSSION**

The substantial range in productivity (579–1001 g m\(^{-2}\)), based on the 40-yr mean county yields, Table 1) in this study provided the variation needed to evaluate the relationship between productivity and YGs. This variation in county yield could be related to environmental conditions, soil characteristics, availability of technology or the farmer’s ability and willingness to deploy the available technology. Using the 40-yr mean yield to characterize productivity should minimize effects of random short-term variation in weather conditions. There was some variation in mean summer (June, July, and August) temperature among states (Kentucky was warmest, followed by Nebraska and Iowa), but the differences were only 1 to 2°C (Egli and Hatfield, 2014) and probably did not contribute much to differences in yield. Kentucky had slightly lower normal summer precipitation (10%) than Iowa (Egli and Hatfield, 2014), which could have contributed to the generally lower yield in Kentucky, but irrigation should have minimized any effects of the lower precipitation in Nebraska. There was not much variation in normal summer precipitation within each state, but there were some north–south gradients in temperature in Iowa and Nebraska (Egli and Hatfield, 2014). It seems unlikely, however, that the substantial variation in the 40-yr mean yield within each state was related to variation in the aboveground environment.

These three states are clustered in a highly developed, sophisticated, high-yielding production system in central United States, making it unlikely that variation in the availability of technology or political and economic conditions that could influence the deployment of technology (Hazell and Wood, 2008; Keating et al., 2010; Licker et al., 2010; Laborte et al., 2012) contributed significantly to the variation in productivity within and among states. Improved technology is a primary driver of yield improvement (see a recent review in Fischer et al. (2014), p. 192–194), so the generally high yield and upward trend during the study period (Egli, 2008a, 2008b; Hatfield, 2010) suggests that many farmers in each state were utilizing the best technology available. It is not possible, however, to eliminate the possibility that some farmers in low-yield counties found it un-economic to employ the same level of technology as in high-yield counties.

Our estimates of APY were based on county yields occurring in the most favorable conditions in the 40-yr period, consequently they represent the collective effort of farmers producing from 3117 to 84,413 ha (7700–208,500 acres) in 2011 with current technology. As such, APY represents the maximum attainable yield estimated within the limits of the available technology and the farmer’s skills (how well do they apply the technology) (Connor et al., 2011, p. 11) when environmental conditions were favorable.

Our APY is probably less than the true potential yield (Evans, 1993, p. 292; Evans and Fischer, 1999) or modeled potential yield (Lobell et al., 2009; van Ittersum et al., 2013). Our APY is no doubt limited by the failure of all farmers in a county to deploy the “best” management practices or by the incomplete elimination of all stress by the favorable environments (e.g., water could still be limiting APY). The APY in 2011 for the county with the highest average yield in Nebraska, however, was only 7% less than the average potential yield (1998–2008) of three irrigated counties in central Nebraska (1520 g m\(^{-2}\)) estimated with a simulation model (Grassini et al., 2011). In the same comparison in Iowa, our APY was 17% less than Fischer et al.’s (2014) estimate of potential yield (1500 g m\(^{-2}\)). The APY of the lowest yielding county in 2011 was 20 and 30% less than the estimates of potential yield for Nebraska and Iowa, respectively. In a very practical sense, APY describes what is possible by a group of farmers in midwestern corn production systems in favorable environmental conditions, so it is closer to the maximum achievable yield described by Licker et al. (2010) or estimates based on maximum farmer yield (Lobell et al., 2009).

The difference between APY and county yield provides a YG estimate (Lobell et al., 2009) that may be smaller than estimates based on modeled potential yield (Lobell et al., 2009; Liang et al., 2011; Laborte et al., 2012; Meng et al., 2013). These YGs may be closer to the exploitable YG (i.e., the difference between the yield of the best farmers and country yield) described by Connor et al. (2011, p. 11). Two advantages of our approach are that it is based on yields that actually occurred, not theoretical yields and it provides an estimate of APY for each of the 40 yr in each county, making it possible to evaluate spatial and temporal YG variation.

Although changes in production technology (improved hybrids and management practices) were mostly responsible for the upward trend in county yields (Egli, 2008a; Fischer et al., 2014), it is unlikely that changes in technology deployment were responsible for the peak yields that provided the basis for the APY estimate. The peak yields were most likely a result of short-term variation in the environment, which in Kentucky and Iowa was probably a result of variation in rainfall (Hatfield et al., 2011).
The mean RYG for the 115 counties varied between approximately 9 and 24% (Fig. 2) which is essentially the same range reported for soybean in the same counties (Egli and Hatfield, 2014). The estimates of van Wart et al. (2013) using simulated potential yield for irrigated and rain-fed corn in the United States were near our maximum levels (23 and 27% of potential yield for irrigated and rain-fed production, respectively). Grussini et al. (2011) reported an average YG of 21% for three irrigated counties in central Nebraska. Fischer et al. (2014) for soybean. The consistently small YGs in the irrigated production in Nebraska is consistent with this argument as soil water holding capacity would be less important when water was not as limiting. The linear relationship between mean county yield (Fig. 5) and NCCPI-AG (which includes soil characteristics) is also consistent with the argument that variation in productivity is related to soil characteristics. Other soil characteristics related to YGs include topographic position (Boling et al., 2010) and soil nutrient status (Affholder et al., 2013). It must be noted, however, that the RYG was not zero in irrigated production in Nebraska and it varied among counties (Fig. 2), which could simply be an indication that water was not the only factor in the plant’s aboveground or belowground environment that influenced the YG in this state and/or that it is difficult (or not economically feasible) to manage irrigation on substantial land areas to eliminate all water stress.

There were no consistent temporal trends in the RYG for the four highest- and lowest-yielding counties in Kentucky. Linear regression of the RYG vs. time was significant (p < 0.10) in only 5 of 32 counties (two with a positive slope and three with a negative slope). There were, however, significant negative trends in 10 of 47 counties in Iowa and 16 of 36 counties in Nebraska. There were no temporal trends for soybean in Kentucky in agreement with the results for corn, but corn showed more evidence for a decline than soybean in Iowa (Egli and Hatfield, 2014) while Nebraska had essentially the same trend for soybean as for corn (16 of 34 counties significant negative slopes). Hatfield (2010), using a similar approach to the one used here, found no temporal trends in YG for corn using average state yields from Iowa, Illinois, Indiana, Kansas, South Dakota, and Texas. An increase in environmental stress, as expected from climate change (Hatfield et al., 2011) could increase the RYG, but the development of stress tolerant hybrids (Tollenaar and Lee, 2002; Campos et al., 2006; Fischer et al., 2014, p. 192–195) or an increase in precipitation (Hatfield et al., 2011) could decrease the RYG over time. These effects cannot be separated with this data set, but it is possible that any increase in environmental stress was cancelled by improved management practices or by the development of hybrids better able to tolerate stress. Interestingly, the clearest trend for a decline in RYG with time of both maize and soybean (Egli and Hatfield, 2014) occurred in Nebraska, the least stressful environment evaluated as shown by higher yields, smaller yield gaps, and less year-to-year variation. Perhaps improved management practices (including irrigation scheduling) made a larger contribution to reducing stress in this relatively low stress environment. The large year-to-year variation in RYG, especially in Kentucky and Iowa (Fig. 3), however, makes any evaluation of temporal trends difficult.

Yield gaps in many production systems can be reduced by increasing inputs or by relatively simple changes in management practices (Tittonell et al., 2008; Liang et al., 2011; Pasuquin et al., 2014), but reducing YGs related to soil characteristics and soil water holding capacity may be more difficult. Irrigation would no doubt reduce the YGs in Kentucky and Iowa if a sustainable source of water is available and the practice is economically feasible. Increasing soil water holding capacity significantly, however, may be a more formidable challenge. The yield increase, on average, if the YG (mean APY – mean county yield, Table 1) was reduced to zero was 23% of the mean county yield in Kentucky, 20% in Iowa, and 13% in Nebraska. Irrigation would probably capture only a proportion of this increase in Kentucky and Iowa, given that the YG was not zero in irrigated production in Nebraska.
There was substantial variation in mean APY (1972–2011) among counties within each state (range in APY, Table 1). This variation occurred in the most favorable environments in the 40-yr period. This variation among counties represents a second YG (i.e., the difference between the maximum average (1972–2011) county APY and the average APY of any other county). The maximum county APY was 30% larger than the minimum (calculated from the ranges in mean APY in Table 1) in Kentucky, 37% in Iowa (only 22% if the second lowest APY was used), but only 14% in Nebraska. Since this second YG occurred in favorable environments, rainfall and soil water availability probably did not play a major role in determining its magnitude, so this second YG may not respond to irrigation in Kentucky and Iowa. Variation in the application of technology or soil characteristics not directly related to soil water storage may be more important. Reducing this second YG may be possible to the extent that management or amendable soil limitations are involved, but, it will be difficult if the gap is related to more intractable soil characteristics.

We previously applied these same techniques to soybean using essentially the same counties and time span (1972–2011) (Egli and Hatfield, 2014). These two crops have few characteristics in common. Soybean, a C3 legume, produces a seed high in oil and protein compared with the high starch kernel produced by C4 maize (Egli, 1998, p. 3). Soybean produces lower yield (ratio of corn to soybean yield averages roughly 2.8 to 3.0, Egli, 2008a), usually has lower economic value per unit harvested area and lower production costs per hectare (www.extension.iastate.edu, accessed 2 July 2014), and requires less management and fewer inputs than corn. In spite of these considerable differences, the mean RYG increased in step with corn (Fig. 5, r = 0.63**). The general association between them suggests that there is some consistency in the response of the two crops to the factors controlling the YG. Yield of the two crops have been increasing at nearly the same rate in Iowa (since 1972) and Kentucky (since 1982) (Egli, 2008a), which is consistent with their similarities in RYGs. The scatter around the one-to-one line suggests, however, that the response to the variation among counties was not entirely the same for the two crops. There was more scatter in the data from Iowa with some counties exhibiting conspicuously lower RYGs for soybean than for corn and others with much larger RYGs for soybean than for corn. Apparently the characteristics that define the differences between these two crops had some effect on their response to stress in certain counties, but the basis of this differential response is not known.

CONCLUSIONS

Corn YG analysis of county yields from 1972 to 2011 in three states with highly sophisticated production systems that differed in productivity produced average RYGs (APY – county yield) ranging from 9 to 24% of the APY. The largest YGs occurred in the least productive counties (i.e., those with the lowest average yields). The large average YGs were related to very low yield in some years, which could be partially related to soil characteristics. The variation in mean APY among counties within a state defined a second YG (highest mean APY– APY of any other county), a gap occurring in favorable environmental conditions. The maximum APY was 30% larger than the minimum APY in Kentucky, 22% in Iowa, and 10% in Nebraska. Eliminating both of these YGs in low-yield counties could increase mean yield by nearly 60% in Kentucky and Iowa, but only 24% in irrigated production in Nebraska.

The magnitude of the first YG and possibly the second could be partially related to variation in soil characteristics. The first YG could probably be reduced by irrigation in Kentucky and Iowa, but the second YG may be more intractable. The magnitude of the RYGs for corn was similar to those for soybean (Egli and Hatfield, 2014) from the same counties.

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