The Contribution of Solar Brightening to the US Maize Yield Trend

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Predictions of crop yield under future climate change are predicated on historical yield trends[1–3], hence it is important to identify the contributors to historical yield gains and their potential for continued increase. The large gains in maize yield in the US Corn Belt have been attributed to agricultural technologies[4], ignoring the potential contribution of solar brightening (decadal-scale increases in incident solar radiation) reported for much of the globe since the mid-1980s. In this study, using a novel biophysical/empirical approach, we show that solar brightening contributed approximately 27% of the US Corn Belt yield trend from 1984 to 2013. Accumulated solar brightening during the post-flowering phase of development of maize increased during the past 3 decades, causing the yield increase that previously had been attributed to agricultural technology. Several factors are believed to cause solar brightening, but their relative importance and future outlook are unknown[5–9], making prediction of continued solar brightening and

its future contribution to yield gain uncertain. Consequently, results of this study call into question the implicit use of historical yield trends in predicting yields under future climate change scenarios.

The United States is the world's largest producer and exporter of maize, consequently maize production in this region has important implications for global supply and pricing. Maize yields, especially in the US Corn Belt, have experienced high rates of gain since the 1930s, attributed to improved agricultural technologies[4,10]. Economic studies of agricultural inputs and outputs in the US suggest that small but significant changes in the adoption and optimization of these technologies have contributed to the consistent annual yield gain[4] of about 2% observed over the historical period. However, climate change studies have predicted that future maize yield in the region will decline due to the impact of rising temperatures[1,2], an outcome that has serious implications for global supply and pricing.

In climate change research, projections of future yields are derived from the extrapolation of historical yield trends combined with estimates of the impact of heat stress on yield due to rising temperatures[1–3]. Although, both historical yield trends and the quantification of heat stress on yield are important for accurately estimating future yields, most research has focused on the impact of heat stress on yields, with little or no attention to the assumptions inherent in projections of historical trends. Studies across various disciplines, i.e., economic, agronomic and physiological studies[4,10,11], have attributed yield gain in the US to the adoption and optimization of improved agricultural technologies such as genetics, agricultural chemicals, chemical application methodology, nutrient management systems, irrigation management practices, and agricultural equipment, implicitly omitting possible contributions of non-technological factors. Consequently, climate change researchers have assumed that through continued investment in agricultural technologies maize yields will continue to rise at historical rates[1–3]. If factors other than technology have also contributed to historical yield gains, the rate of change of these non-technological contributors must also be considered to more accurately estimate future yields.

Among the possible non-technological contributors to variation in maize yield trend (e.g., temperature, precipitation, CO_2, and incident solar radiation), the contribution of decadal-scale changes in incident solar radiation has been overlooked. Mean temperatures in the region of the US Corn Belt under study (see Methods) have not changed significantly during the last three decades as measured either during the pre-flowering phase ($b = 0.004$ ^{O}C $year^{-1}$; $P > 0.85$) or the post-flowering phase ($b = 0.014$ ^{O}C $year^{-1}$; $P > 0.45$) of maize development. Changes in precipitation in the US Midwest in the last few decades were associated with increased frequency of extreme precipitation[12], with consequences for both flooding and drought stress that confound the implication of precipitation changes on maize yields. Since the impact of water stress on maize yields is better correlated to vapor pressure deficit (VPD) than precipitation[13], VPD-adjustment during the flowering period was utilized to correct for changes in precipitation observed during the course of the current study (see Methods). Rising atmospheric CO_2 levels[14] only impact maize yield in the presence of drought, and the level of impact is a function of both the level of CO_2 increase and the degree of drought severity[15–17]. Effects of rising CO_2 under drought stress on yield are ignored in this study because (i) the frequency of drought stress in the current study was relatively low, i.e., VPD adjustment increased mean yield from 130 to 143 bu/ A (6.9 to 7.6 Mg/ha at 0% grain moisture), and (ii) even under drought stress the impact of CO_2 on yield is small (i.e., yield increase of 6%, as estimated from McGrath and Lobell[16], assuming drought stress every year over the 30-year period). Incident solar radiation has been implicitly assumed to be constant at the decadal time scale in most climate change studies. However, large scale monitoring of incident solar radiation that began in the mid-20th century indicated that decadal-level incident solar radiation declined (i.e., solar dimming) since the 1960s and increased (i.e., solar brightening) for most regions of the globe after the mid-1980s[18–21].

Solar brightening (or dimming) is the average increase (or decrease) in solar energy reaching the Earth's surface for a given region and time period as measured by high quality long-term (multi-decadal) surface measurement sites[20] or as inferred in satellite studies[5,18]. Solar brightening at the global scale was reported to be about 2 W m^{-2} per decade, with regional variations from as low as 0.5 W m^{-2} per decade for New Zealand to as high as 8.9 W m^{-2} per decade in Japan for the post-2000 period[6,19]. Studies in the United States also provided clear evidence of solar brightening using surface site analysis, with an average magnitude of approximately 6.6 W m^{-2} per decade, representing some of the largest trends in solar brightening globally[21–23]. Reports have frequently discussed the potential impact of solar brightening and dimming on agricultural productivity, but these impacts have never been quantified[6,18,22,24].

In this study, we examine whether solar brightening has contributed to yield gain since the mid-1980s and quantify the proportion of the US Corn Belt yield trend that can be attributed to solar brightening. Results of this analysis have implications for the contribution of technology to historical yield gains, and the use of historical trends as trajectories for the prediction of maize yields under future climate change scenarios. In addition, the results offer a framework to quantify the impact of decadal-scale changes in solar irradiance on crop production, globally.

The impact of solar brightening on yield was quantified by deconstructing the role of technological and non-technological contributors to yield from thermodynamic principles. Monteith[25] described crop yield in thermodynamic terms in which incident solar radiation is the energy input into the system. In order to utilize variables that are available in large-scale observational studies, Monteith's equation was modified (see Methods) as:

$$\text{Grain Yield} = \text{gRUE} \times Q_{GFP} \quad (1)$$

where Q_{GFP} is accumulated incident solar radiation during the grain-filling period (GFP) and gRUE is the efficiency by which Q_{GFP} is converted into grain yield (equation (M4)). Grain radiation use efficiency (gRUE) was estimated from VPD-adjusted yield corrected for changes in Q_{GFP} from 1984 to 2013 (equation (M5)). A cross validation analysis for equation (1) using predicted and observed VPD-adjusted yield showed a goodness of fit of $R^2 = 0.74$ ($p < 0.0001$) with an intercept not significantly different from 0. Impacts of technology on historical yield gain in equation (1) are manifested through changes in both gRUE and Q_{GFP}. The effect of solar brightening on maize grain yield can be estimated by substituting accumulated solar brightening during the GFP for Q_{GFP} in equation (1).

Results of our study show that more than a quarter of the yield gains between 1984 and 2013 in the US Corn Belt were attributable to solar brightening. Using satellite data of solar irradiance[26,27], we estimate that solar brightening in this region was 8.3 W m^{-2} per decade. Solar brightening values reported from surface sites in the continental United States (6.6 to 7.8 W m^{-2} per decade[21,23], with an uncertainty of +/- 4 W m^{-2} per decade (J.A. Augustine, personal communication)), were consistent with current values despite differences in source of radiation data, regions, and years covered[21,23]. The focus of the current study was on solar brightening of relevance to maize yields, in other words, the solar brightening that occurred during the maize crop's GFP. Solar brightening during the GFP was estimated at 0.06 MJ m^{-2} d^{-1} $year^{-1}$ (6.9 W m^{-2} $decade^{-1}$), which resulted in an increase of 114 MJ m^{-2} in accumulated incident solar radiation during the GFP between 1984 and 2013 (Fig. 1). The impact of solar brightening on maize yield was calculated from estimated accumulated solar brightening during the GFP and gRUE (equation (1)). Both accumulated solar brightening and gRUE increased over the 30-year period. Gains in gRUE presumably were a consequence of improved agronomic and genetic technologies such as increased plant densities, and improved nitrogen use efficiency, functional stay green, and weed and pest control[11,28,29]. The increase in solar brightening in the region was estimated to have contributed 27% to the yield gain between 1984 and 2013 across the 10 states in this study, with an interquartile range of 22 and 33%, which was attributable to a direct effect (24%), i.e., solar brightening at a constant duration of the GFP, and to an interaction between solar brightening and technology (3%), i.e., solar brightening during the increased duration of the GFP since 1984. This corresponds to actual yield increases due to solar brightening ranging from 0 to 31.3 bu/A (Fig. 2), with a mean contribution across the 10 states of 16.1 bu/A (0.85 Mg/ha at 0% grain moisture). Whereas the contribution of technology to yield gain has been overestimated during the 1984-2013 period when solar brightening occurred, it has likely been underestimated during periods when solar dimming occurred (e.g., pre-1980s[18–20]).

If air temperature increased with solar brightening, the impact of solar brightening on yield would be underestimated due to the negative impact of temperatures over 30^{o}C on yield[1–3]. In the current study, there was no significant relationship between the parameters describing the beta distribution of hourly temperatures during the GFP and solar brightening ($P>0.288$; $R^2 = 0.002$ and $P>0.355$; $R^2 = 0.003$ for shape parameters α and β, respectively). The lack of warming in the US Corn Belt between 1984 and 2013 makes the effect of solar brightening on yield gains relatively easy to estimate, in contrast to regions where solar brightening and temperature trends are both significant and correlated.

There are a number of possible reasons why the contribution of solar brightening/dimming to yield trend has previously not been recognized in the literature, despite a wealth of agronomic, physiological and breeding studies conducted to uncover the factors contributing to historical yield gains in North America[10,11,28,30]. The methodologies used in these studies, i.e., side-by-side field trials testing older and newer genetics and/or management technologies, precluded revealing the impact of climatic factors such as incident solar radiation and temperature, and the two and three way interactions of climate, genetics and management on yield. In addition, the lack of availability of multi-decadal solar radiation and phenology data for the Corn Belt until the mid-1980s and a viable quantitative relationship between accumulated incident solar radiation and maize yield all limited the earlier quantification of the impact of solar brightening on yield. It is interesting to note that the reported contribution of improved agronomic practices and genetics to yield gain in observational studies[28] will have unknowingly included effects of solar brightening/dimming, depending on the time period under study.

Predictions of future yields under climate change have assumed that historical rates of yield gain will continue in the future. Research on simulated future crop yields have generally assumed that technology was the primary factor that drove historical yield gains, and that continued investment in technology shall result in the same rates of gain in the future[1–3]. Analysis of the US Agricultural sector between 1948 and 2004 found that total agricultural outputs increased 2.7 times while inputs declined somewhat during the same period[4]. Since yield trends continued after the 1980s despite fewer inputs, much of the yield gains had been attributed to the adoption and optimization of agricultural technologies. The results of the current study show that solar brightening, a non-technological factor, has been an important contributor to maize yields in the US Corn Belt from 1984 to 2013. Hence, yield predictions in climate change research must account for (i) the impact of solar brightening/dimming on historical yield trends and (ii) the potential impact of solar brightening/dimming on crop production under future climate scenarios. It is unlikely that solar brightening will continue at its historical rate in future decades[6], and hence in order to maintain the maize yield trend of the past 3 decades, the current high rate of improvement in agricultural technology must accelerate.

The potential for continued solar brightening is uncertain because of the lack of clarity around the causative agent(s) of solar brightening and the future outlook for these causative agents. Solar brightening is attributable to multiple factors, including decreases in aerosol concentrations, cloud mediated aerosol effects, and direct cloud effects[5,7,8]. Of these possible causes of solar brightening/dimming, aerosol concentrations (which are at least partly attributed to governmental policies such as the Clean Air Act in the US) have been argued to have a prominent role[7,8,31]. China and India experienced solar dimming in the post 2000 period, a phenomenon sometimes attributed to economic and industrial expansion in these regions with limited regulations of atmospheric emissions[8,22,31]. The future outlook of aerosol concentrations is difficult to predict due to regional shifts in industrialization and adoption of air pollution regulations. In western industrialized countries, owing possibly to early adoption of air pollution regulations, limited further brightening is expected since aerosol levels have already stabilized at low values[6,8,32]. In addition, studies in the United States concluded that although aerosols play a role, changes in cloudiness is mostly responsible for the changes in solar irradiance in this region[21,23]. Further, estimates of changes in cloud fields from climate simulations remain highly uncertain as evidenced by comparisons of current climate measurements and climate model simulations[9]. If solar brightening does decline in the future, climate change studies that use historical rates of gain as trajectories for predicting yields would overestimate future yields in the US Corn Belt as well as in other regions with reports of solar brightening.

In contrast to solar brightening that has occurred in the US Corn Belt in recent decades, declining insolation (i.e., solar dimming) has been reported to occur over other regions of the world including China and India, possibly as a consequence of air pollution[8,22,31]. Considering the impact of solar brightening on maize yield, the economic benefits of environmental regulations such as the Clean Air Act may have been underestimated if solar brightening is in part a consequence of reduced air pollution[8]. This raises questions about the possible negative impact that reduced adoption of environmental regulations may have had on the yield of maize and other crops such as rice and wheat in regions such as China and India that have experienced solar dimming.

In conclusion, results of this study show that 27% of maize yield improvement between 1984 and 2013 is attributable to solar brightening, and not due to technology as previously assumed. Since it unlikely that solar brightening will continue at historical rates in future decades[6], it not only raises questions about the use of historical yield trends as trajectories for the prediction of yield in climate change research, but also implies that the current rate of improvement in agricultural technology must accelerate in order to maintain the maize yield trend of the past 3 decades.

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Fig. 1. Accumulated solar brightening during the grain-filling phase of maize across 10 US Corn Belt states between 1984 and 2013. The RMSE of the fitted model was 0.13 MJ m^{-2} and the shading depicts the 95% confidence interval $y= 3.85x - 7639$, $p < 0.0001$.

Fig. 2. Increase in county yields between to 1984 and 2013 that is attributable to solar brightening across 10 US Corn Belt states (counties with >10,000 A of harvested grain corn).

METHODS

This study focused on 10 Corn Belt states that represent more than 80% of total US corn production in 2013: Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Nebraska, Ohio, South Dakota, and Wisconsin. Data on phenology, air temperature, solar radiation, and county production and acreage from 1984 to 2013 was downloaded from public databases (see below).

Data availability. The phenology data that support the findings of this study are available from USDA-NASS (http://quickstats.nass.usda.gov/). Temperature and incident solar radiation data that support the findings of this study were downloaded from the National Oceanic and Atmospheric Administration's (NOAA) Global Historical Climate Data base (GHCN, https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/global-historical-climatology-network-ghcn) and the National Aeronautics and Space Administration's POWER database (NASA, https://power.larc.nasa.gov/cgi-bin/cgiwrap/solar/agro.cgi), produced by the NASA Langley Research Center POWER Project funded through the NASA Earth Science Directorate Applied Science Program, respectively. The yield data in this study were derived from county-level production and harvested grain acreage data obtained from the United States Department of Agriculture's National Agricultural Statistical Service (USDA-NASS, https://www.nass.usda.gov/Statistics_by_Subject/index.php?sector=CROPS). The raw data available from these public databases were used by the authors to derive the data used in the current study. The authors declare that the derived data supporting the findings of this study are available within the paper and its supplementary information files.

Phenology. State-level phenology data from the United States Department of Agriculture's National Agricultural Statistical Service's (USDA-NASS) Crop Progress Report was used in this analysis. The Crop Progress Report is organized weekly in progress percentages related to acres and indicate the progress of field activities or crop development. There were three events from the Crop Progress Report that were used in this study; planting progress, silking progress and maturity progress. The definitions of these stages can be found at http://www.nass.usda.gov/Publications/National_Crop_Progress/Terms_and_Definitions/index.php#corn. Maturity date in the Crop Progress Report coincided with physiological maturity or black layer date[33] as maturity progress occurred approximately 6-7 weeks after silking and approximately 4 weeks prior to harvest maturity. The total lifecycle of the crop was considered to span from planting to physiological maturity. A phenological stage was considered to have been reached when 50% of the acreage was at that stage, based on a logistic model. The logistic function modeled the fraction of acres in each state at a given phenological stage as a function of time (day of year). The logistic function was expressed as:

$$F_{stg}(t) = \frac{1}{1 + exp(-b(t - c))} \quad \text{(M1)}$$

where t is the day of year (time); $F_{stg}(t)$ is the fraction of area at a given stage at day of year t; b is rate of change in the fraction of area versus date; and c represents the day of year in which F_{stg} is equal to 50%. Parameters b and c were obtained through non-linear least squares and used for estimation of date (t) when F_{stg} is 50%.

Climate. The National Oceanic and Atmospheric Administration's GHCN and the NASA POWER databases were selected to generate daily temperatures and solar radiation values respectively based on their relative performance in studies which compared the relative accuracy of various weather data bases[27,34]. Only those GHCN stations for which there were no missing data over the entire period of study were used in this study. Daily maximum and minimum temperatures were the averages across all such stations within each crop reporting district (CRD). County solar radiation values were based on the pixel nearest the county centroid. Solar radiation accumulated during pre- and post-silking periods was calculated by multiplying mean solar radiation for days without missing data multiplied with the number of days in the pre-silking and post-silking periods for each county. Counties with more than 5 percent missing data for daily solar radiation were deemed as missing data. Mean accumulated solar radiation of all applicable counties within a CRD was weighted using the proportion of harvested CRD maize acreage over harvested state maize acreage. Total accumulated solar radiation for a state was calculated as the sum of weighted CRD values for the state. Accumulated incident solar radiation over the pre-flowering period and the grain-filling period (GFP) for each state was calculated as the sum of incident solar radiation from planting date to silking date and from 1 day post-silking to maturity, respectively.

Yield and VPD adjustment. All yield data used in our analyses were based on harvested maize grain acreage. State-level yields were obtained by aggregating weighed (based on harvested grain acres), county-level data from the United States Department of Agriculture's National Agricultural Statistical Service (USDA-NASS) for the period from 1984 to 2013. County level production and acreage data were accessed only for counties with more than 10,000 acres of harvested maize grain acres to ensure that only major production areas within the selected states were used for the analysis. Yields in each county was calculated as total production divided by harvested grain acres.

Impact of water stress on weighed yield was estimated using vapor pressure deficit (VPD) values[13] during a 4-week period centered at flowering, a period when the crop is the most sensitive to water stress[35]. Daily VPD was estimated at the CRD level as the difference between the mean saturated vapor pressure (0.6107 * exp(17.269 x T / (237.3 + T))) at daily maximum and minimum temperatures[13]. The VPD data were used to calculate a yield data time series for each state with the influence of moisture stress removed by modeling yield as a linear function of time using VPD as a covariate. From this model, fitted values and residuals were extracted as were predicted values of yield under non-stressful VPD conditions. Non-stressful VPD conditions were quantified as the median VPD value minus one interquartile range observed during the 1983-2013 growing seasons. These values (i.e., fitted values, residuals, and predicted yield under non-stressful conditions) were aggregated to the state-level, and then used to rescale the yield data to produce a time series that maintained its correlation with time yet was invariant to VPD, following the methodology used in yield risk assessment[36–38]. The goodness of fit for the relationship between maize yield and incident solar radiation during the GFP (Q_{GFP}) increased from R^2=0.48 to R^2=0.52 after VPD adjustment.

Yield model. In order to quantify the potential impact of solar brightening on yield and its mechanism of action, we deconstructed the role of technological and non-technological contributors to yield from first principles and developed a novel yield model, equation (1). Monteith[25] described crop yield in thermodynamic terms in which incident solar radiation is the energy input into the system. Using this biophysical approach, grain yield can be quantified as the product of the intercepted solar radiation by the crop (Q_I), the conversion of this intercepted energy into biomass (radiation use efficiency, RUE), and the partitioning of the biomass into grain (harvest index, HI).

$$\text{Grain Yield} = \text{HI} \times \int_{planting}^{maturity} (Q_A \times RUE)\, dt \qquad \text{(M2)}$$

where grain yield is grain mass at 0% moisture per unit land area at maturity, and HI is the quotient of grain yield and biomass (above-ground crop phytomass at 0% moisture per unit land area at maturity) at physiological maturity, and RUE is the quotient of accumulated biomass and accumulated intercepted solar radiation during the whole or parts of the life cycle. The variables in equation (M2) require extensive field measurements that are only available in small, experimental data sets, which generally preclude the use of biophysical models in large-scale observational studies. Equation (1) was developed from equation (M2) to incorporate variables that are quantifiable in large-scale observational studies while retaining its biophysical basis: grain yield, incident solar radiation, phenology, and a RUE variable.

Results of a meta-analysis show that grain yield is highly associated with dry matter accumulation during the GFP[11,39–45](Fig. S1). Data were obtained from field experiments that included multiple maize hybrids[11,39–44], and maize grown at a range of plant densities[11,42,44], soil N levels[39,40,42,43], and levels of weed interference[39,43,44], in which dry matter accumulation during the GFP was estimated from destructive whole-plant sampling of >= 2 m^2 well-bordered areas at both silking and maturity, and grain yield was measured at maturity[11,39–44]; each datum in Fig. S1 represents the mean of >= 3 replications/year across 1-3 years. The proportion of dry matter accumulated during the GFP that was allocated to the grain in these studies varied with hybrid and crop management, and was greater in hybrids released after 1990 than in those released prior to 1990[45], but overall the relationship was close to 1:1 (Fig. S1). Hence, grain yield equals dry matter accumulation during the GFP. As dry matter accumulation equals the product of accumulated intercepted radiation and RUE (e.g., $\int_{silking}^{maturity}(Q_I \times RUE)\,dt$), grain yield in this study was estimated as the product of accumulated incident solar radiation during the GFP (Q_{GFP}) and grain radiation use efficiency (gRUE): Grain Yield =

Q_{GFP} × gRUE (equation (1)). In equation (1), gRUE incorporates the proportion of incident radiation that is intercepted, the conversion of intercepted radiation into dry matter, and the proportion of the dry matter allocated to the grain (which is 100%, see Fig. S1). Equation (1) is supported by empirical data (Fig. S2). The relationship between grain yield and accumulated incident solar radiation appears to be specific to the growth stage: grain yield and solar radiation accumulated during the GFP were linearly related in 10 states of the US Corn Belt across the 1984-2013 period, but were not related during the pre-flowering period (Fig. S2), consistent with earlier reports on wheat and rice[46].

Contribution of solar brightening to yield improvement 1984-2013. Yield due to solar brightening was estimated by substituting accumulated solar brightening for Q_{GFP} in equation (1). Solar brightening during the GFP (MJ m^{-2} d^{-1} $year^{-1}$) in each state was estimated from the annual change in accumulated incident solar radiation over a fixed period that was bracketed by the earliest silking date and latest maturity date for each state across the 30-year period divided by the number of days of the fixed period. Accumulated solar brightening during the GFP (MJ m^{-2}) across the 1984-2013 period increased due to both increased solar brightening and lengthening of the GFP and was estimated as:

$$SB_{s,y} = \left(\frac{d(SRfixed_s)}{dy} \times \Delta y \times GFP_{s,y} \right) \qquad \text{(M3)}$$

where $SB_{s,y}$ is accumulated solar brightening during the GFP in State *s* and Year *y* since 1984 (MJ m^{-2}), d($SRfixed_s$)/dy is solar brightening, i.e., the slope of incident solar radiation during a (fixed) period bracketed by the earliest silking date and the latest maturity date vs. year between 1984 and 2013 in State *s* (MJ m^{-2} day^{-1} $year^{-1}$), Δy is no. years elapsed since 1984 (years), and $GFP_{s,y}$ is the duration of the GFP in State *s* and Year *y* (days) estimated from linear regression of GFP vs. year between 1984 and 2013. Accumulated solar brightening during the GFP increased due to solar brightening multiplied by the duration of the GFP in 1984 (direct effect) and due to solar brightening multiplied by the increase in duration of the GFP after 1984 (i.e., the solar brightening x technology interaction effect). Mean $SB_{s,2013}$ across 10 states was 114 MJ m^{-2}, with an interquartile range of 97 and 122 MJ m^{-2}.

Grain radiation use efficiency (gRUE) between 1984 and 2013 was estimated from VPD-adjusted grain yield adjusted to remove the impact of the increase in Q_{GFP}. The increase in Q_{GFP} was the result of increased GFP (due to improved technology) and solar brightening. $YieldQ_s$ was estimated by modeling VPD-adjusted yield as a linear function of time using Q_{GFP} as a covariate, similar to the procedure described above to estimate VPD-adjusted yield.

$$gRUE_{s,y} = \frac{Yield_{s,1984} + \frac{d(YieldQ_s)}{dy} \times \Delta y}{(Q_{GFP})_{s,1984}} \qquad \text{(M4)}$$

where $gRUE_{s,y}$ is the grain radiation use efficiency in State *s* and Year *y* [bu/A (MJ $m^{-2})^{-1}$], $Yield_{s,1984}$ is VPD-adjusted grain yield in State *s* in 1984 (bu/A), $d(YieldQ_s)/dy$ is the slope of the linear regression of solar-radiation adjusted yield vs. year from 1984 to 2013 in State *s* [bu/A $(year)^{-1}$], and $(Q_{GFP})_{s,1984}$ is accumulated incident solar radiation during the GFP (MJ m^{-2}) in State *s* in 1984. Grain yield and Q_{GFP} in 1984 were estimated from linear regression of these variables across the 1984-2013 period in each state. Mean $gRUE_{s,2013}$ across 10 states was 0.141 bu/A (MJ $m^{-2})^{-1}$, equivalent to 0.75 g MJ^{-1} (grain at 0% moisture), with an interquartile range of 0.137 and 0.143 bu/A (MJ $m^{-2})^{-1}$.

The contribution of solar brightening to yield improvement since 1984 in State *s* in Year *y* ($\%SB_{s,y}$) is computed using SB_s and $gRUE_{s,y}$ from equations (M3) and (M4) as:

$$\%SB_{s,y} = 100 \times \left[\frac{SB_{s,y} \times gRUE_{s,y}}{\Delta Yield_{s,y}}\right] \qquad \text{(M5)}$$

where $d(SB_s)/dy$ is the slope of accumulated solar brightening during the GFP in State *s* vs. year (MJ $m^{-2}year^{-1}$) and $\Delta Yield_{s,y}$ is the regressed increase in VPD-adjusted yield in State *s* and Year *y* relative to 1984 (bu/A), which is a function of gRUE and Q_{GFP} in State *s* in Year *y*. The mean increase in VPD-adjusted yield between 1984 and 2013 across the 10 states ($\Delta Yield_{s,2013}$) was 60 bu/A (3.2 Mg/ha; grain at 0% moisture), with an interquartile range of 55 and 62 bu/A. The contributions of solar brightening to yield improvement since 1984 do not differ between actual and VPD-adjusted yield, because differences in gRUE due to VPD-adjustment are expressed in both the numerator and denominator of equation (M5).

Statistics. Grain yield estimated from equation (1) was cross validated utilizing a Monte Carlo simulation (merTools package[47] in R) utilizing 10,000 iterations on observed and predicted VPD-adjusted yield (R^2=0.74, p<0.0001). The relationship between solar brightening and air temperature during the GFP were examined using distribution modeling techniques. This methodology allows entire distribution of temperatures observed during the GFP to be modeled as a function of solar brightening. For each state-year the entire distribution of hourly temperatures during the GFP were calibrated to a beta distribution and the parameters describing the shape of the distribution (α and β shape parameters) were stored and merged with the solar brightening data. Changes in the GFP temperature distribution during the 1984-2013 period were then modeled using shape parameters α and β as the dependent variables and solar brightening as the independent variable.

Data used to generate Figs. 1 and S2 were subjected to analysis using a random coefficient/multi-level modeling approach with state serving as the subject effect. This modeling approach allows the parameters of the model (i.e., intercept and slopes) to vary over the subject effects. Analysis was conducted with R[48] using the LME4 package[49]. The 95% prediction interval (gray shade) shown in Figures 1 and S2b was computed via a Monte Carlo simulation (each using 10,000 iterations) with the merTools package[47] in R. The increase in county yield that is attributable to solar brightening from 1984 to 2013 (Fig. 2) was estimated from the contribution of solar brightening to yield gain as a proportion of total yield gain in each state and the county yield differential during this period using linear regression of county yield vs. year. To generate Fig. S1, the grain yield attribute (at 0% moisture) from the meta-analysis dataset was regressed against accumulated dry matter during the GFP. The model parameters were saved and used to compute a 95% prediction interval using the 'predict' function in R[22]. The resulting interval and predicted values were then plotted with the original data to produce the shaded area in Fig. S1.

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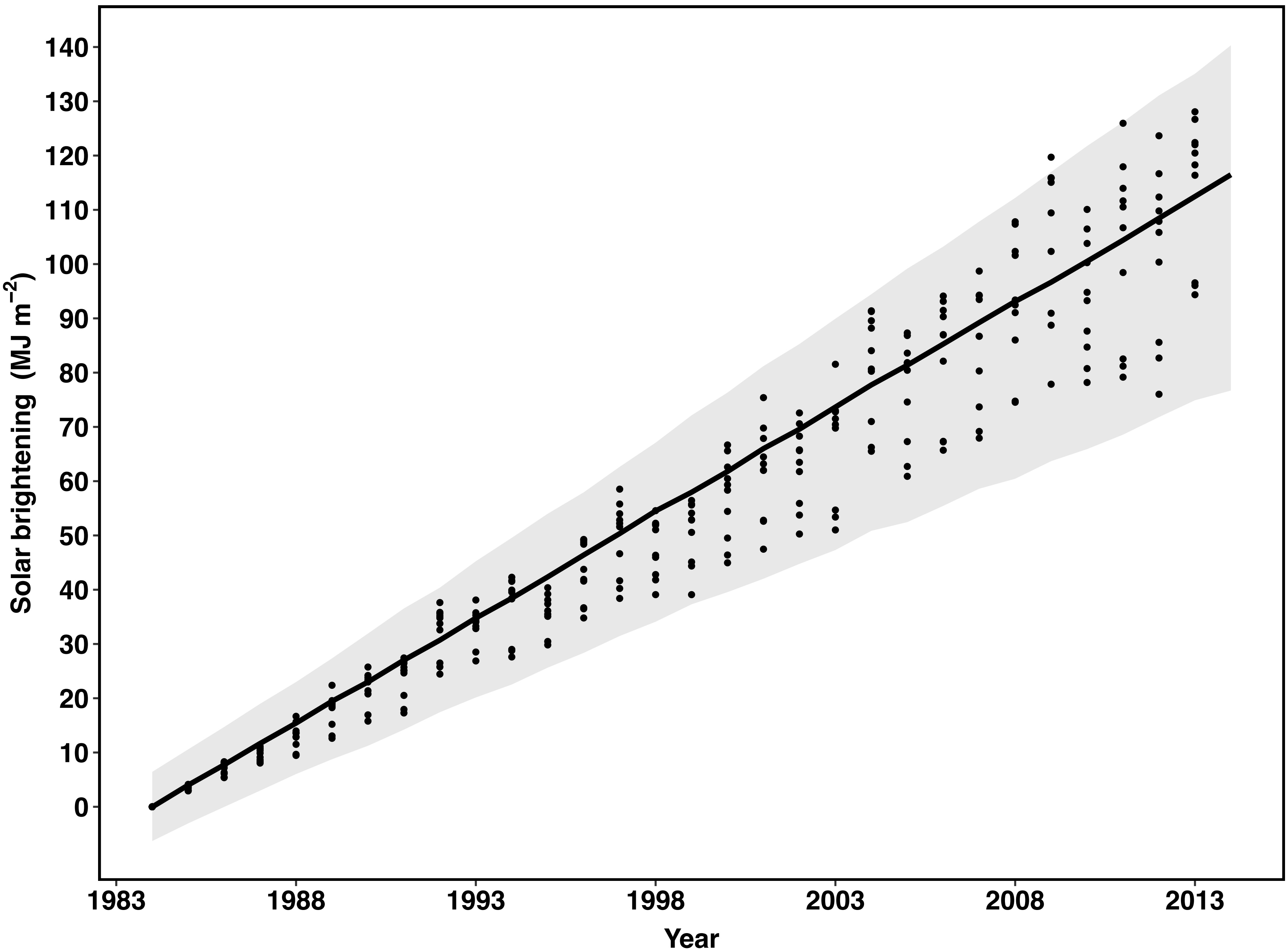
FIGURES

The Contribution of Solar Brightening to the US Maize Yield Trend

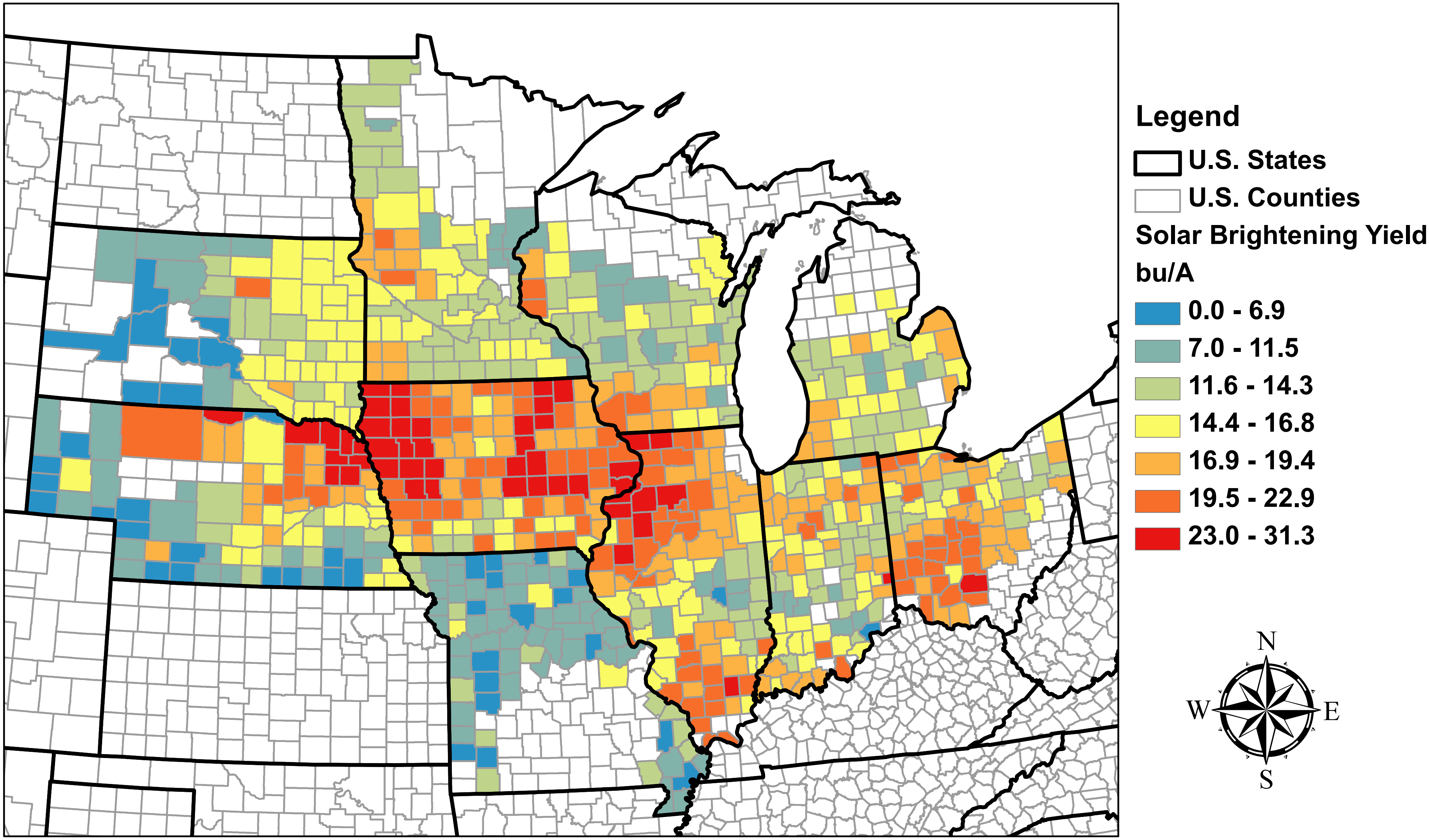
Fig. 1. Accumulated solar brightening during the grain-filling phase of maize across 10 US Corn Belt states between 1984 and 2013. The RMSE of the fitted model was 0.13 MJ m^{-2} and the shading depicts the 95% confidence interval y= 3.85*x* - 7639, $p < 0.0001$.

Fig. 2. Increase in county yields between to 1984 and 2013 that is attributable to solar brightening across 10 US Corn Belt states (counties with >10,000 A of harvested grain corn).



Solar brightening (MJ m−2)
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
1983
1988
1993
1998
2003
2008
2013
Year

Fig. 1



Legend
U.S. States
U.S. Counties
Solar Brightening Yield
bu/A
0.0 - 6.9
7.0 - 11.5
11.6 - 14.3
14.4 - 16.8
16.9 - 19.4
19.5 - 22.9
23.0 - 31.3
N
W
E
S

Fig. 2

SUPPLEMENTAL INFORMATION

The Contribution of Solar Brightening to the US Maize Yield Trend

Fig. S1. Relationship between grain yield (0% moisture) and dry matter accumulated during the grain-filling period. Meta analyses of field experiments that included multiple hybrids, plant densities, N amendments, and weed interference[10–16]. Shaded area represents 95% confidence interval ($p < 0.0001$).

Fig. S2. Relationship between grain yield (VPD-adjusted) and accumulated incident solar radiation during a) pre-flowering and b) grain-filling phases of development. The root mean square error (RMSE) of the fitted model for the GFP was 0.60 bu A^{-1} and shading depicts the 95% confidence interval, $y = 0.16x - 28.5$, $p<0.0001$.

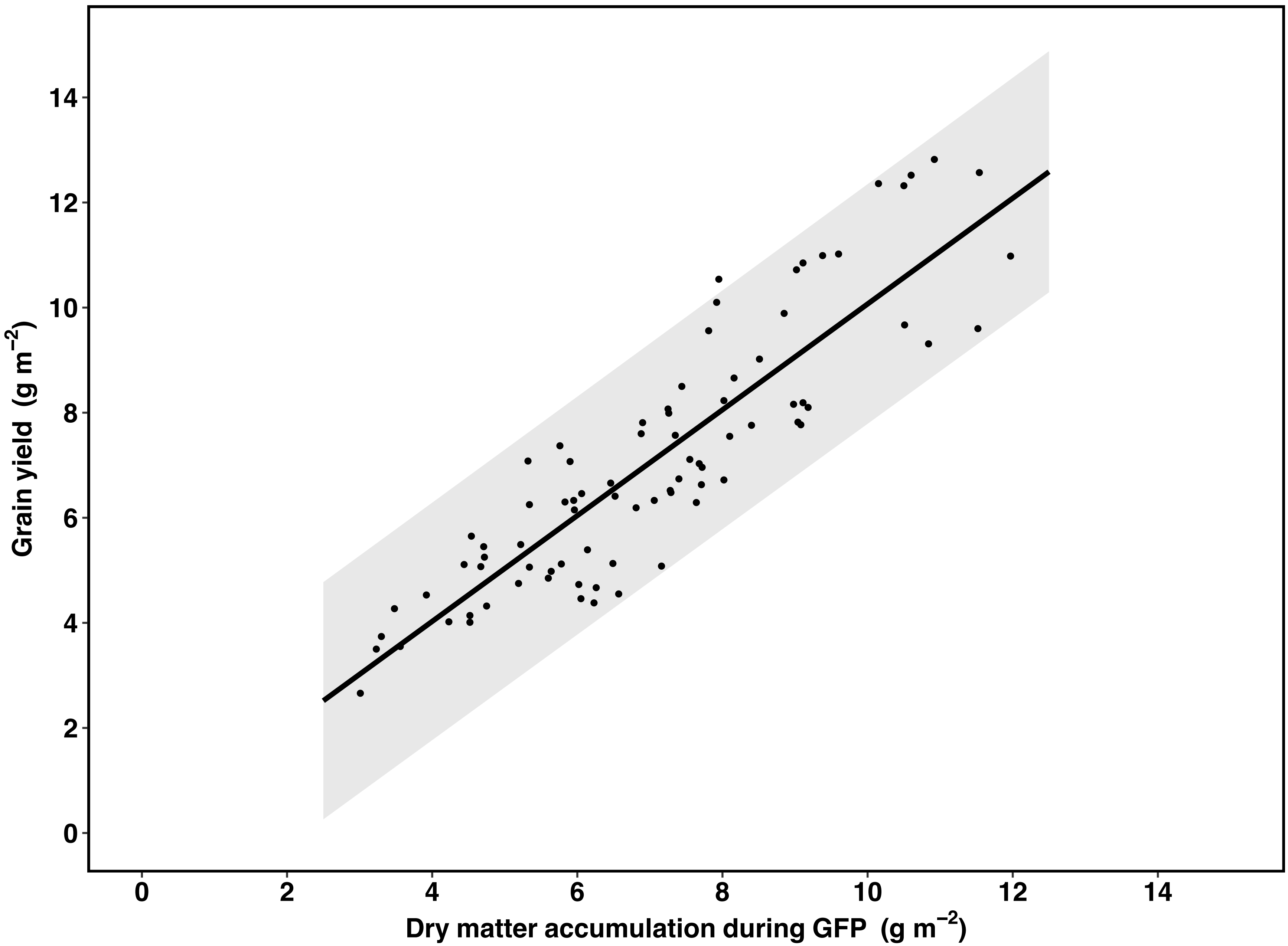

Grain yield (g m−2)
0
2
4
6
8
10
12
14
0
2
4
6
8
10
12
14
Dry matter accumulation during GFP (g m−2)

Fig. S1

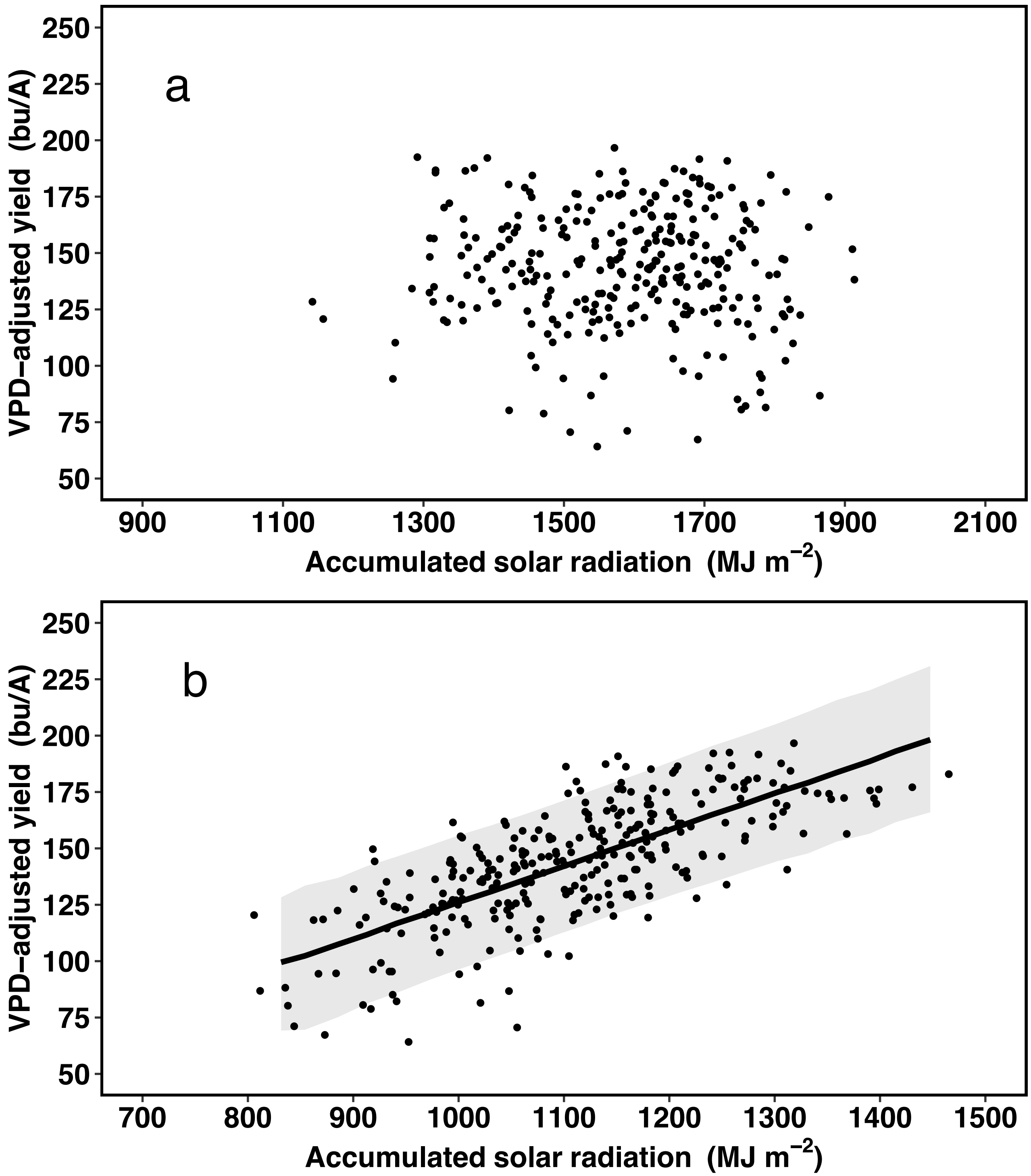

a
VPD−adjusted yield (bu/A)
250
225
200
175
150
125
100
75
50
900
1100
1300
1500
1700
1900
2100
Accumulated solar radiation (MJ m−2)
b
VPD−adjusted yield (bu/A)
250
225
200
175
150
125
100
75
50
700
800
900
1000
1100
1200
1300
1400
1500
Accumulated solar radiation (MJ m−2)

Fig. S2