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Source: Canadian Journal of Plant Science, 103(1) : 93-100

Published By: Canadian Science Publishing

URL: https://doi.org/10.1139/cjps-2022-0104

Canadian Journal of
Plant Science

Article

Precipitation irregularity and solar radiation play a role in determining short-season soybean yield

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Abstract

Climate change, resulting from increased atmospheric CO_2, will affect temperature and precipitation amount and regularity. Changes in solar radiation have been observed in the recent past. Precipitation irregularity is a measure of rainfall distribution during a growing season (calculated as the standard error of the slope from regression of cumulative precipitation on day of the growing season). We investigated whether precipitation irregularity and solar radiation contributed to soybean yield. Fourteen short-season cultivars, released from 1930 to 1992, were grown from 1993 to 2019 at Ottawa, Canada. Stepwise multiple linear regression was used to investigate the contribution to seed yield of precipitation irregularity and solar radiation, and also previously modeled parameters genetic improvement, annual [CO_2], and cumulative precipitation and average minimum temperature during the vegetative, flowering and podding, and seed filling growth stages. While solar radiation and precipitation irregularity did not trend over the years of our study and precipitation irregularity was not related to growing season precipitation, both were significant factors in our model, accounting for 2.5% and 6.5%, respectively, of the seed yield variability. Precipitation during all three stages were similar as they each accounted for 4%–7% of seed yield variability. We observed contrasting temperature effects where higher minimum temperature during vegetative and seed filling reduced yield, while during flowering and podding increased yield. Estimated yield improvement due to elevated [CO_2] was 7.8 kg ha^{-1} ppm^{-1} and to genetic improvement over time was 7.1 kg ha^{-1} $year^{-1}$. Over the extremes of our study we found that precipitation irregularity could cause up to a 30% yield reduction.

Key words: soybean, *Glycine max*, precipitation irregularity, solar radiation, precipitation, temperature

Introduction

In describing changes in annual or growing season cumulative precipitation, the timing of onset of rains, the intensity of rainfall events, and (or) the temporal distribution or irregularity of rainfall can all be considered (Mardero et al. 2020). Monjo and Martin-Vide (2016) provided an overview of methods for quantifying precipitation irregularity. There are many ways to quantify precipitation irregularity such as comparing actual cumulative precipitation to equidistributional precipitation, that is when rainfall is equally distributed across the growing season. A further approach sums the number of rainy days in a period or takes the intensity and duration of rainfall events into consideration (Monjo and Martin-Vide 2016). While climate change, mediated by the increase in atmospheric CO_2, is resulting in higher air temperature, it is also affecting precipitation causing wide fluctuations in rainfall that can result in both flooding and drought (Easterling et al. 2000; Fischer et al. 2014; Pendergrass and Knutti 2018) including Sloat et al. (2018) who found that both within- and between-year variability for rainfall has been increasing in global pasture lands. Eastern North America is considered a climate change hotspot, in part, due to precipitation variability (Giorgi 2006). Modeling of crop yields in light of climate variability demonstrates effects of climate parameters on crop yield and provides data for policies to mitigate future stresses (Ray et al. 2015; Kukal and Irmak 2018). Precipitation irregularity has been modeled on a regional basis in the southeast US and precipitation irregularity tables provided for risk management and water use management (Sohoulande et al. 2019). Crop modeling with increased precipitation variability predicted effects on yield depending on soil properties (Riha et al. 1996). Much modeling is devoted to understanding changing climate parameters on regional crop yield risk. A retrospective analysis of rice yields in India found that increased precipitation irregularity (measured as decreased rainy days) had a negative effect on seed yield (Fishman 2016). When this concept was applied to projections in the future, where increasing precipitation was originally predicted to increase rice yield by 2%, the combination of increased precipitation with increased precipitation irregularity predicted an 11% decline in seed yield, where the precipitation increase was negated by greater precipitation irregularity (Fishman 2016). While modeling of crop yield using climate parameters on a global or regional basis is well represented in the literature, the use of precipitation variation parameters to understanding seed yield in field crop experiments is limited.

A study to estimate the effect of solar brightening on US maize yield (Tollenaar et al. 2017) was undertaken since solar radiation has been increasing over time in the US (Long et al. 2009). Solar radiation during maize seed filling was estimated to be rising at 0.06 MJ m^{-2} day^{-1} $year^{-1}$ from 1984 to 2013 (Tollenaar et al. 2017). This solar brightening was estimated to be responsible for 27% of the US Corn Belt yield increase during the study period (Tollenaar et al. 2017). A comparison of the relative importance of growing season solar radiation for maize and soybean found solar radiation somewhat more important for soybean yield in the US compared to maize yield but less important than temperature for both maize and soybean (Hoffman et al. 2020). A recent study reported changes in US solar radiation where solar brightening occurred from 1996 to 2012 at a rate of 7.36 W m^{-2} $decade^{-1}$ but solar radiation started decreasing in 2013 at the rate of −3.9 W m^{-2} $decade^{-1}$ through 2019 (Augustine and Hodges 2021).

Using a data set from a series of old to new cultivars grown from 1993 to 2004 at Ottawa, Canada, we found that short-season soybean was most responsive to changes in precipitation during the flower and seed development stages (Morrison et al. 2006). Further investigation found that increased precipitation increased soybean yield during all three phases of growth, i.e., vegetative, flowering and podding, and seed filling (Cober and Morrison 2019). Our objective was to investigate the contribution of precipitation irregularity to soybean yield using our data set of a series of old to new cultivars grown since 1993 with the hypothesis that increased precipitation irregularity decreases soybean yield. In addition, since our data set encompasses a period of solar brightening and solar dimming, our objective was to determine the role of growing season solar radiation on soybean yield.

Materials and methods

Fourteen short-season cultivars representing seven decades of soybean breeding, 1930–1992 (see Morrison et al. 2000 for cultivar details), were grown in randomized complete block yield trials with four replications from 1993 to 2019 at Ottawa, ON, Canada (45°23′N lat.). Agronomy details for this trial were provided in our most recent report on this study (Cober and Morrison 2019) but a brief description is provided here. Plot row number varied some years but there were at least four rows spaced 40 cm apart and 6 m long in each plot. Data from 2005 were not included in this analysis due to a seed mixture error. Seed was inoculated with *Bradyrhizobium japonicum* and planted at 50 seeds m^{-2} to a depth of 1.5–2.0 cm using the same seeder for the duration of the experiment. The target seeding date was 20 May each year. P and K fertilizer was broadcast pre-plant and incorporated according to soil tests. Weeds were controlled using recommended herbicides and manually hoeing during the growing season. Until 2011, the experiment was grown on a Grenville loam (Cryochrepts, Eutrochrepts, Canadian classification). Post 2011, the experiment was grown on a Matilda sandy loam (Cryochrepts, Eutrochrepts, Hapludolls). Mean phenology over all cultivars was used to separate each growing season into vegetative (planting to first flower), flowering and podding (first flower to full pod), and seed filling (full pod to full maturity) periods. At maturity, plots were combine harvested, the seed was cleaned and weighed, and the seed yield adjusted to 13% moisture by weight.

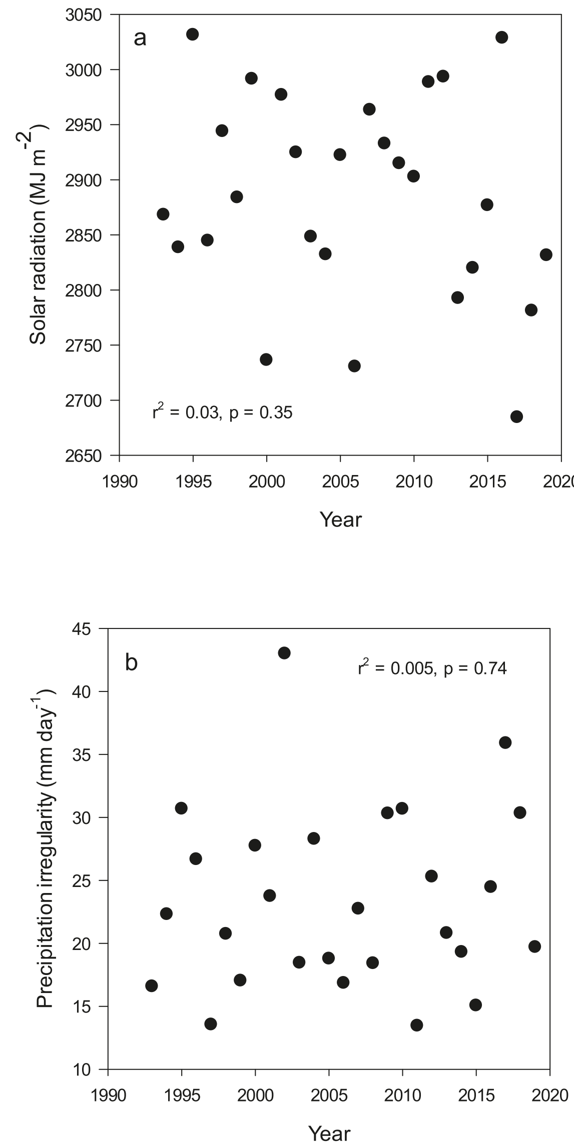
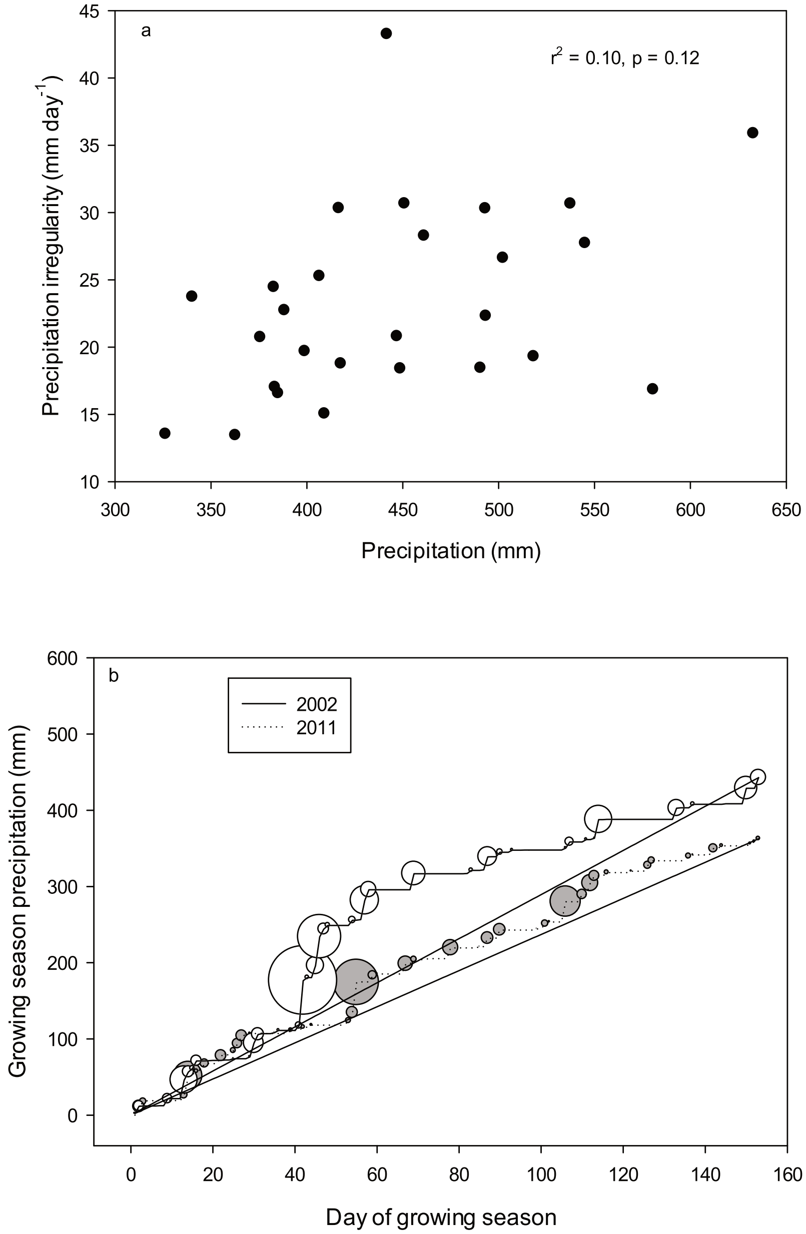


Fig. 1. Growing season (May–September) (*a*) solar radiation and (*b*) precipitation irregularity over years, at Ottawa, Canada, 1993–2019. Results for a linear regression model are shown in each panel.

Weather parameters were described previously (Cober and Morrison 2019) but briefly, in-season (May–September) daily minimum temperature, precipitation, and solar radiation were observed at a nearby weather station on the Central Experimental Farm. Atmospheric CO_2 concentration data were from the annual mean Mauna Loa [CO_2] observations (Dr. Pieter Tans, NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends/) and Dr. Ralph Keeling, Scripps Institution of Oceanography (scrippsco2.ucsd.edu/)). Precipitation irregularity was calculated as the standard error of the slope of the regression of the cumulative precipitation on day of the growing season. Seasonal solar radiation was the sum of daily values.

Fig. 2. Growing season (May–September) (*a*) precipitation irregularity versus growing season precipitation at Ottawa, Canada, 1993–2019 (results for a linear regression model are shown), and (*b*) precipitation versus day of the growing season for the highest (2002) and lowest (2011) years for precipitation irregularity with relative daily rainfall shown with bubbles and growing season equidistribution shown for each year with solid lines.



Collinearity between parameters was examined before carrying out multiple linear regression using Pearson correlation analysis in Proc Corr of SAS Studio 3.81 (Cary NC). A moderate correlation was declared when $0.3 < |r| \leq 0.5$ and a strong correlation when $|r| > 0.5$. A threshold of $|r| < 0.5$ was used to flag parameters in the multiple linear regression following Wilmsmeyer et al. (2019). Stepwise multiple linear regression (Proc Reg, STEPWISE, SAS Studio 3.81) was used to investigate the factors that were significant in determining soybean seed yield including genetic improvement rate (the slope of the line of yield plotted over year of release), annual [CO_2], precipitation irregularity over the growing season, cumulative precipitation, and average minimum temperature during the three phenological phases, vegetative, flowering and podding, and seed filling, and seasonal solar radiation. Maximum temperature was found to be collinear to minimum temperature in our previous work (Cober and Morrison 2019) and was excluded from the regression. The stepwise multiple regression process added significant ($p < 0.15$) parameters to the model and provided partial R^2, mean effects, and standard errors for each significant parameter. Collinearity was also examined following multiple linear regression analysis using the variance inflation factor where values >10, or more conservatively >5, indicated problems with collinearity (Tamura et al. 2019) especially for parameters that had

Table 1. Pearson correlation coefficients between weather variables from 1993 to 2019 at Ottawa, Canada.

	V ppt	FP ppt	SF ppt	V Tmin	FP Tmin	SF Tmin	Pir	SR
$[CO_2]$	−0.18	−0.008	0.05	0.44	0.086	0.004	0.07	−0.21
V ppt		−0.08	−0.20	−0.04	−0.29	−0.42	0.28	−0.45
FP ppt			−0.09	0.05	0.03	−0.25	0.13	−0.26
SF ppt				0.05	0.03	−0.25	0.13	−0.26
V Tmin					0.10	−0.08	0.11	−0.35
FP Tmin						0.19	0.09	0.15
SF Tmin							0.07	0.56
Pir								−0.13

Note: Correlations exceeding the limit for collinearity ($|r| > 0.5$) are shaded dark grey while moderate correlations are shaded light grey ($0.3 < |r| < 0.5$). Phenology stages: V, vegetative; FP, flowering and podding; SF, seed filling. Weather parameters: Pir, precipitation irregularity; ppt, precipitation; SR, solar radiation; Tmin, mean minimum temperature (°C). Abbreviation: SF Tmin, seed filling minimum temperature.

Table 2. Stepwise multiple linear regression analysis of soybean seed yield due to genetic gain due to plant breeding, growing season precipitation irregularity and solar radiation, annual $[CO_2]$, growth phase precipitation and minimum temperature parameters from trials of 14 old to newer cultivars grown from 1993 to 2019 at Ottawa, Canada.

	Seed yield (kg ha^{-1})					
Variable[a]	Partial R^2	Estimate	SE	T ratio	p value	Variance inflation factor
Intercept		−22 391	2924	−7.66	<0.0001	0
Genetic gain, kg ha^{-1} year^{-1}	0.043	7.11	1.24	5.74	<0.0001	1.00000
Ppt irregularity, mm day^{-1}	0.061	−25.6	3.84	−6.66	<0.0001	1.32359
Solar radiation, MJ m^{-2}	0.025	1.47	0.37	3.95	<0.0001	2.10910
$[CO_2]$, ppm	0.018	7.76	1.70	4.57	<0.0001	1.40307
V ppt, mm	0.042	6.74	0.77	8.84	<0.0001	2.25175
FP ppt, mm	0.056	5.94	0.59	10.01	<0.0001	1.35549
SF ppt, mm	0.065	5.11	0.55	9.22	<0.0001	1.29535
V Tmin, °C	0.015	−123.7	36.7	−3.37	0.0008	1.53117
FP Tmin, °C	0.12	321.2	31.9	10.06	<0.0001	1.15790
SF Tmin, °C	0.065	−79.6	22.7	−3.50	0.0005	1.67886
Model p value	<0.0001					
R^2	0.543					
Adjusted R^2	0.530					
RMSE	449					

[a]Variables were included in the model if the p value <0.15. Phenology stages: V, vegetative; FP, flowering and podding; and SF, seed filling. Weather parameters: ppt, precipitation (mm); Tmin, mean minimum temperature (°C). Abbreviation: SF Tmin, seed filling minimum temperature.

$|r| > 0.5$. Proc Reg was used to perform simple linear regression.

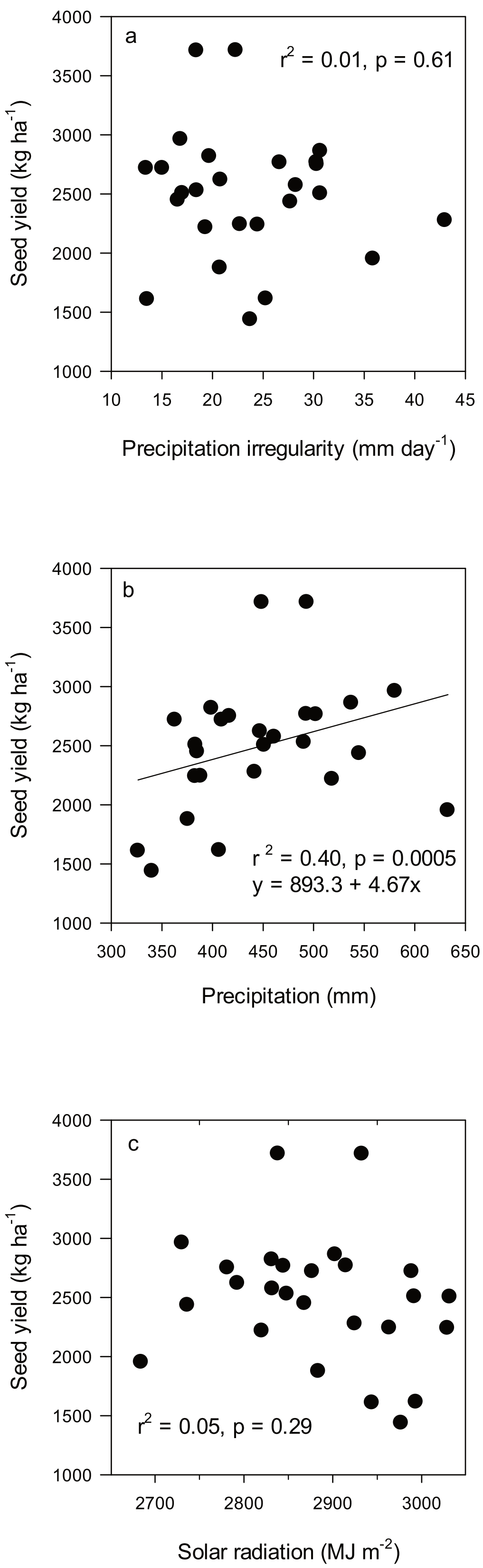
Results and discussion

Precipitation irregularity, calculated as the standard error of the slope of cumulative rainfall regressed on day of the growing season, varied from 13.4 to 43.3 mm day^{-1} at Ottawa, Canada over the years 1993–2019 (Fig. 1*b*). Precipitation irregularity did not trend over the years of our study (Fig. 1*b*) and was not related to the total amount of precipitation during the growing season (Fig. 2*a*). Precipitation irregularity was visualized for the highest (2002) and lowest (2011) years in Fig. 2*b*.

In the stepwise multiple linear regression analysis, factors were first examined for collinearity using correlation analysis. Solar radiation and seed filling minimum temperature exceeded the correlation limit of 0.5 (Table 1); however, examining the variance inflation factor following multiple linear regression showed no concern for collinearity for these two parameters or for any other parameters (Table 2).

Precipitation irregularity was as important as precipitation at each growth stage in our model, accounting for 6% of the variability for seed yield (Table 2). Seed yield dropped 25.6 kg ha^{-1} for every unit increase in precipitation irregularity in the multiple linear model (Table 2); however, this was not significant in a simple linear regression analysis of seed yield on precipitation irregularity (Fig. 3*a*). Over the duration of our study, precipitation irregularity ranged about 30 units (Fig. 1*b*) resulting in the potential for a surprisingly large difference in yield, 765 kg ha^{-1}, which equals ~30% yield loss. In an examination of rice production and weather parameters, Fishman (2016) used temperature and precipitation in India from 1970 to 2003, and also added measures of

Fig. 3. Soybean seed yield versus (*a*) growing season (May–September) precipitation irregularity, (*b*) growing season precipitation, and (*c*) growing season solar radiation at Ottawa, Canada 1993–2019. Results for a linear regression model are shown in each panel.



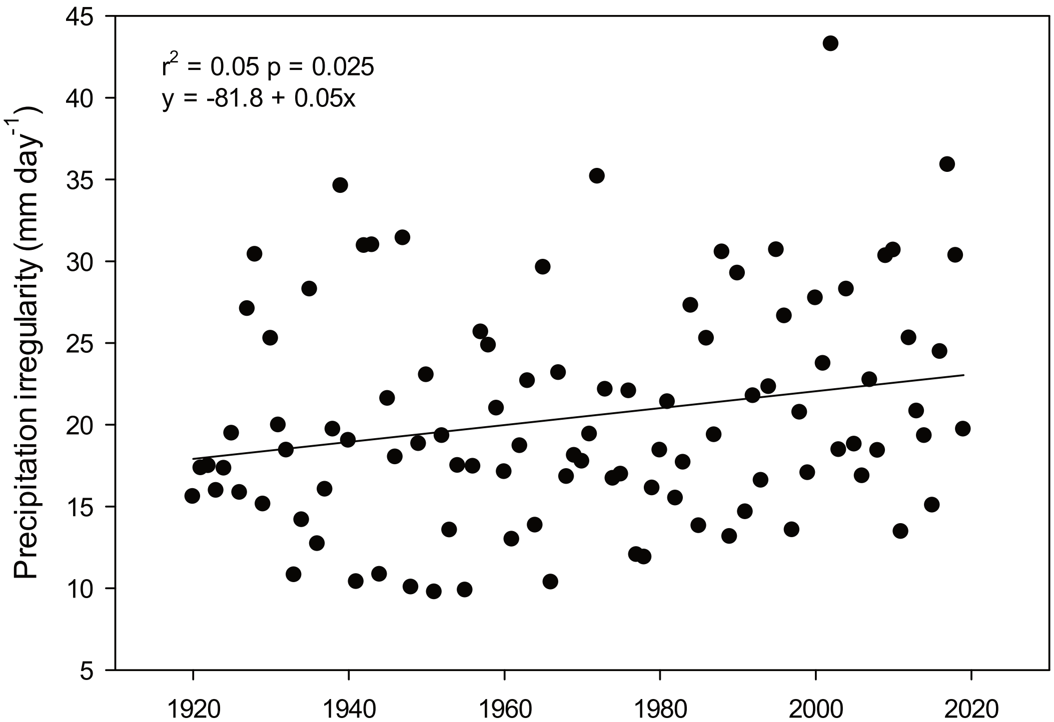
precipitation irregularity including number of rainy days, number of extreme rainfall events, and duration of the longest dry spell to the analysis to distinguish between growing seasons with similar total precipitation but different rainfall distributions. The number of rainy days was proposed as the most useful addition to the yield model (Fishman 2016). To extend their work, yield was predicted to 2050 and whereas a yield increase of 2% was expected from increased precipitation, including precipitation irregularity in the model predicted a yield decrease of 11% (Fishman 2016). A one location–year experiment with barley (*Hordeum vulgare* L.) did not find a seed yield difference when precipitation levels were maintained but frequency varied with rainout shelters and irrigation (Högy et al. 2013); however site-years would need to be increased to draw meaningful conclusions on seed yield. Our multiple linear regression model suggests that over our data set from 1993 to 2019 we observed the potential for a 30% yield loss due to precipitation irregularity. We believe this is the first multiple environment field study observing the effect of precipitation irregularity on soybean seed yield.

Precipitation effects during all three growth phases were similar in they each accounted for 4%–7% of seed yield variability (Table 2). Increased seasonal precipitation resulted in increased yield with a range of 5–7 kg ha^{-1} per mm of rain (Table 2) compared with 2–3 kg ha^{-1} mm^{-1} in our previous analysis (Cober and Morrison 2019). When we examined total growing season precipitation with simple linear regression, the seed yield increase was estimated at 4.7 kg ha^{-1} per mm of rain (Fig. 3*b*). Estimates of yield increase due to rainfall or irrigation in Wisconsin (Kucharik and Serbin 2008) and Nebraska (Specht et al. 2001) ranged from 5.0 to 2.8 kg ha^{-1} mm^{-1}, respectively. In our study, the combined effects of precipitation during vegetative, flowering and podding, and seed filling explained 16.3% of seed yield variation compared to 6.1% for precipitation irregularity (Table 2).

Solar radiation did not show a linear trend over the years of our study period (Fig. 1*a*). Fitting a quadratic equation to our data showed a maximum for solar radiation in 2004 ($r^2 = 0.07$), while more widespread US analyses showed solar radiation started decreasing in 2013 (Augustine and Hodges 2021). In our multiple linear regression model, solar radiation accounted for 2.5% of seed yield variation with yield increases of 1.5 kg ha^{-1} for each MJ m^{-2} (Table 2), however, simple linear regression with seed yield was not significant (Fig. 3*b*). In modeling soybean yield across the US, growing season solar radiation was as important as growing season precipitation for seed yield (Hoffman et al. 2020), while precipitation explained about six times more of the seed yield variation than solar radiation in our study (Table 2).

In earlier publications using the historical cultivar set, we found that plant breeding in Canada has resulted in varieties with reduced maximum height, and maximum leaf area index as well as greater photosynthetic rate per leaf and harvest index (seed mass/total biomass) (Morrison et al. 1999, 2000). In other words modern soybean cultivars were more efficient at intercepting solar radiation and converting it to seed yield. Koester et al. (2014) also found that yield improvement in historical cultivars from the US was the result of increased light interception and its conversion to biomass and seed yield.

Fig. 4. Growing season (May–September) precipitation irregularity versus growing season precipitation, at Ottawa, Canada from 1920 to 2019. Results for a linear regression model are shown.



Radiation use efficiency reflects a crop's ability to utilize solar radiation and is calculated as biomass accumulation in a given period of time over intercepted radiation. Radiation use efficiency is a measure of the biomass produced from the amount of radiation intercepted. It is used to predict yield by converting radiation use efficiency to yield based on known values of harvest index. In a study done in maximum yielding environments, Van Roekel and Purcell (2014) found no relationship between radiation use efficiency and yield but concluded that radiation use efficiency needs to be maintained through the duration of plant growth to maintain high yields.

We observed contrasting temperature effects where higher temperature during the vegetative and seed filling growth stages reduced yield, and during flowering and podding increased yield (Table 2) similar to our previous work (Cober and Morrison 2019). Seed filling temperature was the most important parameter accounting for 12% of seed yield variance (Table 2). In a study in the US Midwest (southern Minnesota, Iowa to central Illinois, and Indiana), temperature during early reproductive growth (June) was the most important parameter in estimating soybean yield (Joshi et al. 2021). An artificial intelligence analysis of US soybean reported yield increases with increased minimum temperature during grain filling (Hoffman et al. 2020), similar to our finding of growth phase specificity for minimum temperature. Minimum temperature during grain filling was relatively more important than minimum temperature over the whole growing season. Yield improvement due to elevated [CO_2] was estimated at 7.8 kg ha^{-1} ppm^{-1} (Table 2), which is higher than our previous estimate of 4.3 kg ha^{-1} ppm^{-1} (Cober and Morrison 2019) but within the range of other values in the literature of 2.2 (Sakurai et al. 2014) to 13.3 kg ha^{-1} ppm^{-1} (Bunce 2014).

Yield improvements due to plant breeding were estimated using the same set of cultivars at 7.1 kg ha^{-1} year^{-1} in this study compared to our initial estimate of 11.1 kg ha^{-1} year^{-1} (Voldeng et al. 1997) and our recent estimate of 8.0 kg ha^{-1} year^{-1} (Cober and Morrison 2019). Our estimates of genetic improvement for seed yield from plant breeding are decreasing as we add more environmental factors into our model, from the initial study which only considered year of release, to the current study, which added precipitation irregularity and solar radiation to precipitation, minimum temperature, [CO_2], and year of release.

While we did not see an increase in precipitation irregularity over the years of this study (1993–2019; Fig. 1*b*), when we examined growing season precipitation irregularity over the past 100 years at Ottawa, we observed a trend for increasing precipitation irregularity (Fig. 4). The years of this study captured the high value of 43.3 for precipitation irregularity in 2002 but not the lowest value over 100 years (13.4 in our study and 9.8 in 1951). Annual precipitation in Canada has increased by about 20% since 1948 (Vincent et al. 2018) with more falling in the north than in southern regions. Model projections estimate that future precipitation will increase by 10% in all seasons in the short term, although as air temperatures rise in the latter part of the century, summer precipitation in southern Canada will decrease by up to 30% (Zhang et al. 2019). Additionally, extreme precipitation events leading to flooding or periodic drought will increase and higher summer evapotranspiration will result from lower precipitation and higher air temperature. This may lead to higher rates of increase of precipitation irregularity in the future. Brevedan and Egli (2003) showed that even short periods of drought stress during critical phases of development such as flowering or seed filling can lead to irreversible seed yield losses. In soybean, as available soil water decreases N_2 fixation rates decline prior to photosynthesis and biomass accumulation (Sinclair et al. 2007). Therefore, it is not only the total amount of seasonal precipitation that affects yield but the regularity of rainfall events that maintain soil water levels above threshold levels required to maintain N_2 fixation, photosynthesis, and growth. Plant breeders may need to investigate the genetic control of response to irregular precipitation to develop climate resilient cultivars.

In conclusion, when we added precipitation irregularity and solar radiation to our previous model with genotype (as year of release), [CO_2], temperature, and precipitation, we found that precipitation irregularity and solar radiation played an important role in determining soybean seed yield. During our study, precipitation irregularity ranged about 30 units resulting in the potential for a surprisingly large 765 kg ha^{-1} or 30% yield loss. We believe this is the first report of the effect of precipitation irregularity on soybean seed yield.

Article information

History dates

Received: 26 May 2022
Accepted: 26 November 2022
Accepted manuscript online: 30 November 2022
Version of record online: 12 January 2023

Notes

This paper is part of a Collection championed by the Canadian Society of Agronomy and entitled “Cropping system adaptation for enhanced resilience to climate change in cold climate regions”.

Copyright

Data availability

On request from the authors, data will be made available.

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Visualization: ERC
Writing – original draft: ERC
Writing – review & editing: ERC, MJM

Competing interests

The authors declare that there is no conflict of interest.

Funding information

This research was supported by Agriculture and Agri-Food Canada.

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