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Evaluating opportunities for an increased role of winter crops as adaptation to climate change in dryland cropping systems of the U.S. Inland Pacific Northwest

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Abstract The long-term sustainability of wheat-based dryland cropping systems in the Inland Pacific Northwest (IPNW) of the United States depends on how these systems adapt to climate change. Climate models project warming with slight increases in winter precipitation but drier summers for the IPNW. These conditions combined with elevated atmospheric CO_2, which promote crop growth and improve transpiration-use efficiency, may be beneficial for cropping systems in the IPNW and may provide regional opportunities for agricultural diversification and intensification. Crop modeling simulation under future climatic conditions showed increased wheat productivity for the IPNW for most of the century. Water use by winter wheat was projected to decrease significantly in higher and intermediate precipitation zones and increase slightly in drier locations, but with winter crops utilizing significantly more water overall than spring crops. Crop diversification with inclusion of winter crops other than wheat is a possibility depending on agronomic and economic considerations, while substitution of

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winter for spring crops appeared feasible only in high precipitation areas. Increased weed pressure, higher pest populations, expanded ranges of biotic stressors, and agronomic, plant breeding, economic, technology, and other factors will influence what production systems eventually prevail under future climatic conditions in the region.

Keywords Alternative rotations · Crop modeling · Global climate models · Representative concentration pathways

1 Introduction

Anthropogenic climate change in mid-to-high latitudes will lead to accelerated development and earlier maturation of crops (e.g., Cleland et al. 2007). Resultant shortened growing seasons should in principle reduce biomass production and yields; however, biomass of dryland crops in the Inland Pacific Northwest (IPNW) of the United States is typically limited by water rather than by length of the growing season. The primary driver of anthropogenic climate change is increased concentrations of greenhouse gases, including carbon dioxide. Elevated CO_2 concentration [CO_2] has two important effects on plants: (a) increased photosynthesis, biomass, and yields of C_3 plants (minimal effect on C_4 plants); and (b) decreased stomatal conductance (both in C_3 and C_4 plants), leading to reduced crop water loss (Ainsworth and Rogers 2007). The resulting increase in transpiration-use efficiency (TUE = grams of biomass produced per kilogram of water transpired) may mitigate or overcome detrimental effects of warming for water-limited systems. The effect of [CO_2] on plant growth and stomatal conductance ("CO_2 fertilization") has been demonstrated in open field experiments using Free-Air CO_2 Enrichment (FACE) systems, which simulate agricultural conditions (Long et al. 2004). Earlier FACE experiments (Tubiello et al. 1999) demonstrated that well-watered wheat yield increased 7 to 9% when [CO_2] was elevated from 350 to 550 ppm.

Future crop evapotranspiration (ET) will be affected by the interaction of temperature (increased evaporative demand but shorter crop season) and [CO_2] (reduced transpiration). Increased TUE under future environmental conditions might lead to greater benefits for water-limited crops. FACE experiments (only accounting for CO_2 effects) in Arizona showed consistently around 6.7% lower spring wheat ET at 550 ppm compared to ambient 360 ppm (Kimball et al. 1999). The dependence on soil water of crop growth gain under elevated [CO_2] has been extensively documented, particularly for water-limited cropping systems (e.g., Grant et al. 1999; Manderscheid and Weigel 2007). While studies have shown yield increases under elevated [CO_2], the increases in yield for wheat are notably greater for systems under water stress. For example, wheat yield increased 44 and 74% for wet and dry treatments, respectively, ([CO_2] elevated from ~346 to 825 ppm) (Chaudhuri et al. 1990). Others report wheat yield increases of ~10% for wet conditions, and over 44% for dry conditions ([CO_2] elevated from 365 to 645 ppm) (Manderscheid and Weigel 2007), and 7 to 9% with ample water and 17 to 20% under water stress ([CO_2] changed from 350 to 550 ppm) (Tubiello et al. 1999).

These findings suggest that, in the IPNW, CO_2 fertilization may mitigate and even overcome the negative effects on agricultural production typically associated with global warming (e.g., Asseng et al. 2015). We hypothesize that earlier maturity and accelerated growth due to more favorable winter and spring temperatures, combined with greater TUE, will create favorable conditions for winter crops, and provide opportunities for replacing lower-yielding spring crops with winter crops, thus intensifying and diversifying IPNW cropping systems. We used computer simulation and climate projections for the region to evaluate these possibilities.

2 Methodology

Five sites in the IPNW were selected for the study (Table 1). The sites were distributed among annual cropping, annual crop-fallow transition, and crop-fallow Agroecological Classes (AEC) (Huggins et al. 2015), and they included annual precipitation amounts ranging from 253 to 748 mm and annual average temperatures from 7.6 to 9.8 °C. The wettest two locations, Moscow Mt. and Pullman, were along the eastern extent of the INPW wheat-growing region; the driest location was Lind. The warmest temperatures were at the lowest elevation site, Lind, and the coolest temperatures were at either Moscow Mt. (summer) or Wilke (fall through spring).

Simulations were accomplished using CropSyst (Stöckle et al. 2003, 2014), v. 5.0. CropSyst is a process-based hourly/daily time step cropping systems model that produces projections of productivity and environmental impact of crop rotations in response to climate, soil, and agronomic management. The model has been used worldwide for many applications (see Stöckle et al. 2014) including climate change impact studies (e.g., Bocchiola et al. 2013; Sommer et al. 2013; Stöckle et al. 2010). For this study, the nitrogen module in CropSyst was disabled and reduced tillage management was implemented. Harvest of winter wheat in the annual crop/fallow transition zone and in the annual cropping zone was followed by a chisel plow operation. Seedbed preparation in all zones consisted of a sweep plow operation. While many wheat varieties are used in the region, a "representative" wheat cultivar was defined for this system analysis that conformed to the typical growing season and canopy ground cover in each AEC, characteristics that are important for determining resource capture and productivity. Simulated crops were calibrated using local yield records and known phenology and historic weather records (Papendick 1996; Schillinger et al. 2006; Schillinger, personal communication). Crop phenological parameters were adjusted to approximate flowering and maturity dates typical of the AEC within which a particular site was located. Small adjustments were made to transpiration-use efficiency to fine-tune the simulated yield. All other crop parameters were kept at their default values for wheat. Simulated yields for the historic period closely matched observed data that were available (Table 1) indicating that the crop parameters were adequate for the study region.

Baseline crop rotations for each site represented rotations traditionally used in the area. Alternative rotations (Table 1) were developed for two of the three AECs that would test (1) whether crop production could be intensified by reducing the amount of time the land was fallow or (2) whether alternative crops might be incorporated into the rotation to diversify production. Winter peas have been of interest for dryland rotations for several decades (Huggins and Pan 1991), but the lack of food quality peas has precluded their widespread adoption. However, recent development of high-yielding, edible winter pea cultivars (Chen et al. 2006; McGee et al. 2014) suggests that winter peas are likely to be a viable addition to dryland crop rotations in the future, so we included winter peas as an alternative crop for the rotation systems in our modeling.

Climate simulations from global climate models (GCMs) in the Coupled Model Intercomparison Project, Phase 5 (CMIP5) were statistically downscaled over the contiguous United States using the Multivariate Adaptive Constructed Analogs method (Abatzoglou and Brown 2012) with a joint bias correction of daily temperature and precipitation. Downscaled data

Table 1 Characteristics of five Inland Pacific Northwest sites used for a study of climate change impact on future dryland crop production along with simulated baseline and alternative crop rotations

Location	Latitude, longitude	Precipitation (mm)	Temperature (°C)	Soil textural class	Agroecological class	Baseline crop rotation[a]	Simulated historic and measured[b] (in parentheses) yields (Mg ha^{-1})		Alternative crop rotation[a]
							WW	SW	
Moscow Mt.	46.7710° N, 116.9380° W	748	8.0	Silty clay loam	Annual cropping	SW-SP-WW	6.56 (6.40)	4.37 (4.07)	WW-WW-WP
Pullman	46.7797° N, 117.0851° W	572	8.5	Silty clay loam	Annual cropping	SW-SP-WW	6.30 (6.40)	4.11 (4.07)	WW-WW-WP
St. John	47.0833° N, 117.5833° W	442	9.1	Coarse silt loam	Annual crop/fallow transition	SF-WW-SW	6.10 (6.16)	3.58 (3.59)	SF-WW-WP SW-SP-WW
Wilke	47.6522° N, 118.1354° W	345	7.6	Coarse silt loam	Annual crop/fallow transition	SF-WW-SW	5.06 (5.40)	2.84 (2.73)	SF-WW-WP SW-SP-WW
Lind	47.0000° N, 118.5667° W	253	9.8	Coarse silt loam	Crop/fallow	SF-WW	3.09 (2.96)		

Precipitation and temperature are annual averages over the period 1980–2005. Modeled historic yields for winter wheat and spring wheat (averaged over 1985–2010) were simulated using the baseline crop rotation with historic weather data for each site assuming atmospheric CO_2 concentration of 360 ppm

[a] *SF* summer fallow, *SP* spring pea, *SW* spring wheat, *WP* winter pea, *WW* winter wheat

[b] Data from http://smallgrains.wsu.edu/variety/2015-data/. Accessed 1-27-17. Measured yields from within the same rainfall zone as the tabled location, but not necessarily from the same location. Data are averaged over 2011–2015

were trained using the 1/24th degree resolution gridded surface meteorological dataset of Abatzoglou (2013).

Climate model simulations were downscaled for the historical (1950–2005) and future (2006–2099) climate experiments, with the latter using Representative Concentration Pathway (RCP) experiments RCP 4.5, which represents a future of moderate climate mitigation policy, and RCP 8.5, which represents a future of no climate policy. CO_2 concentrations rise to 538 and 927 ppm by 2100 in RCP 4.5 and RCP 8.5, respectively (Riahi et al. 2011; Thomson et al. 2011). We examined projected changes in climate from 12 climate models that credibly simulated historical climate of the study region (Rupp et al. 2013) to account for the inherent uncertainty in climate change projections.

Baseline cropping system simulations were run for the period 1980 to 2010, with [CO_2] set at 360 ppm, approximating observed [CO_2] of the mid-1990s. We ran future scenarios from 2011 to 2099 and considered runs where [CO_2] changed according to the respective RCP, and with [CO_2] held constant at 360 ppm, the latter to isolate the effects arising purely from physical changes in climate. Within an AEC, winter wheat (WW) was sown on the same day of the year. Seeding spring crops, however, depended on the mean temperature for a 15-day window. The soil data required came from the USDA-NRCS STATSGO soil database. Soil at all sites was either a silty clay loam or a coarse silt loam (Table 1), with no soil depth limitations and a water holding capacity averaging 0.185 $m^3\ m^{-3}$, providing good storage capacity for the available precipitation. For both the historic and future runs, the first 4 years of the simulation were discarded so that the data reported were not influenced by the simulation's initial conditions. Within each scenario, the rotation ran with a staggered starting crop so that every crop in the rotation was simulated in every year of the weather file.

3 Results and discussion

3.1 Future environmental conditions in the IPNW

Most GCMs project slight increases in annual precipitation by the mid-twenty-first century 2040–2069, with a multi-model mean increase of +5.8% (Fig. 1); however, anthropogenically driven increases in regional precipitation are generally small relative to the interannual

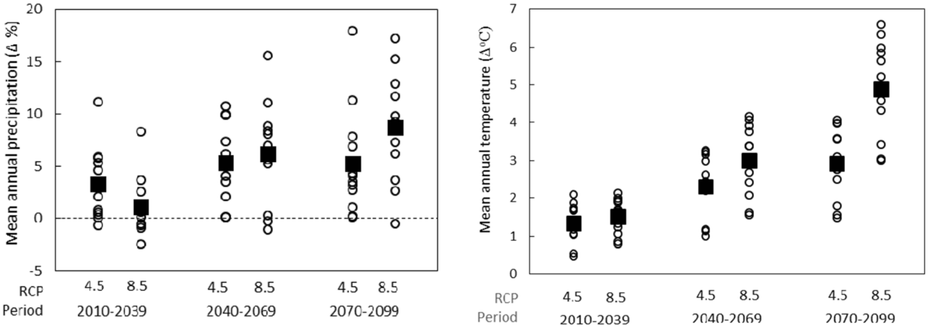

Fig. 1 Projected changes in mean annual precipitation and temperature for three time periods and two representative concentration pathways (RCPs) in the Inland Pacific Northwest. Projections are based on 12 global climate models (GCMs) which are represented by *circles*. Within a time period and RCP, the *square* represents the mean of the ensemble of GCMs

variability. The increase in annual precipitation is predominantly associated with larger increases in winter (Dec–Feb) and spring (Mar–May) precipitation totals (+10%). By contrast, summer precipitation is projected to decline slightly (−10%).

Mean annual and seasonal temperatures increase across all climate models by the mid-twenty-first century with an average warming of +2.7 °C by 2040–2069 (intermodel range +1.0 to +4.2 °C) (Fig. 1). Models robustly show amplified (+20%) warming rates during the summer months that correspond with an increase in the sensible to latent heat flux as soil moisture decreases (Rupp et al. submitted).

3.2 Climate change effects without CO_2 elevation

These simulations were conducted keeping [CO_2] constant at 360 ppm while temperature and precipitation changed as projected by the different GCMs. We focus here on the effect of increasing temperature, which is more dramatic than precipitation changes. Warming has several effects on crop growth including shortening of the growth cycle, potentially damaging heat during grain set (Ferris et al. 1998; Siebert et al. 2014), increased atmospheric evaporative demand, and changes in photosynthesis (both increasing and reducing it).

Warming resulted in approximately a 40-day reduction in the growing season length for winter wheat across all locations for RCP 8.5 and about 20 days for RCP 4.5. In the case of spring wheat, there was year-to-year variation but no consistent trend of season length. Spring crops were sown (and matured) earlier in the year as temperature increased, thus adapting to warmer weather and generally preserving the duration of the growing season.

Due to earlier maturation of winter and spring wheat with warming, anthesis was also earlier mitigating the detrimental impacts from extreme heat during anthesis that affects grain set and yield. For winter wheat, another feature of increasing temperature was a decrease of overwinter growth-reducing low temperatures (Parker and Abatzoglou 2016), so biomass production and canopy development both increased.

Simulated climate change with no [CO_2] elevation effect on wheat (Fig. 2) showed a more positive outlook for yields in the IPNW than normally assumed for warming scenarios (Asseng et al. 2015). For RCP 8.5, spring and winter wheat yields first increased or remained steady and then declined by mid-century to levels similar (Moscow Mt., Pullman, and Wilke) or below (St. John, only winter wheat) initial values; the exception was Lind which showed some gain. Yields of winter wheat and spring wheat were preserved throughout the century for RCP 4.5, except for a 10% winter wheat decline at St. John. Yield increases were driven by some increase in precipitation, with crops early in the century able to utilize the available soil water even as growing seasons were shortening. By mid-century, the decline in season length limited the use of soil water, with yields declining while some of the soil water was increasingly left unused. The exception was Lind, a severely water-limited site, where crops were able to utilize the increasing available water even with shorter growing seasons. An exceptional case was St. John, with a relatively high annual historical precipitation of 442 mm (Table 1) and where a fallow year preceded WW resulting in high available soil water at the beginning of the growing season. This condition resulted in stable yields early in the century, but combined with high temperature (annual average of 9.1 °C, the second-warmest of all sites—Table 1) shortened the growing season length, which was already about 16 days shorter than in Wilke. By the 2050s, St. John yields were reduced below those in Wilke (Fig. 2).

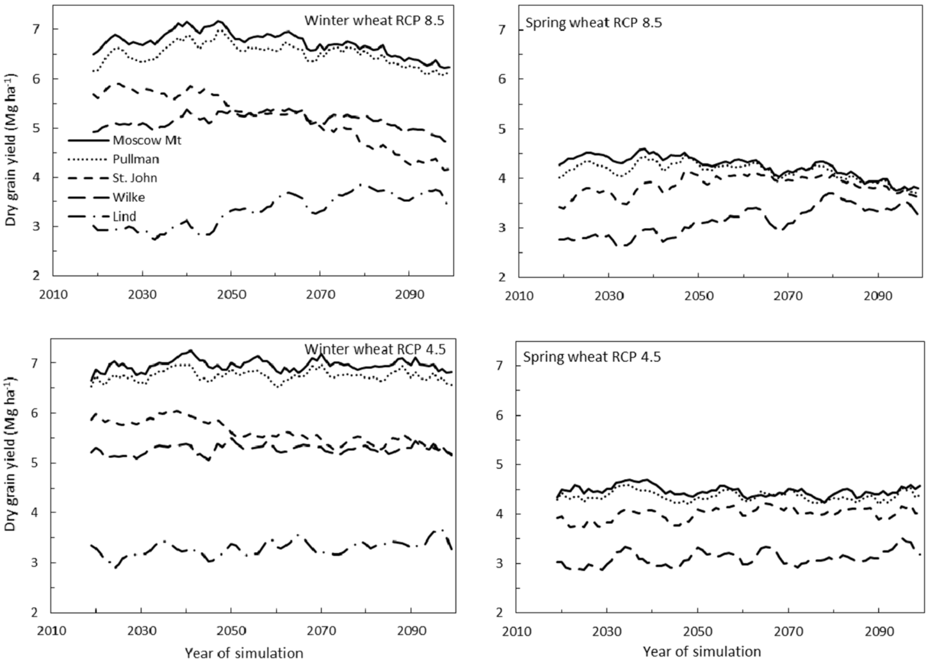

Fig. 2 Projected dry grain yields (5-year running averages) of winter and spring wheat for the period 2019 to 2100 and RCP 4.5 and RCP 8.5 climate projection scenarios under dryland conditions at five locations in the Inland Pacific Northwest. Simulation includes only climate change effects, with [CO_2] kept constant at 360 ppm. See Table 1 for simulated historic wheat yields

3.3 Climate change and elevated CO_2 interactions

These interactions depend on plant responses to [CO_2]. Photosynthetic response to [CO_2] follows a typical saturation response. Experimental data of biomass gain as a function of [CO_2] show a similar saturation response when biomass is normalized relative to its value at 370 ppm (i.e., biomass ratio = 1.0 at 370 ppm). The biomass ratio saturates at about 1.25 when [CO_2] >1000 ppm (Reuveni and Bugbee 1997). Stomatal conductance decreases with increased [CO_2] until it levels off at around 1000 ppm (Allen 1990). As [CO_2] is projected to remain below 1000 ppm through 2100 under RCP 8.5, the CO_2 fertilization effect should favor wheat yields; however, continued increases in [CO_2] and warming beyond the end of the century should result in a steady decline of wheat yields in the IPNW.

Figure 3 shows the trend of future winter and spring wheat yields at all locations, including the effects of climate change and projected [CO_2]. For winter wheat under RCP 8.5, significant gains in yields are projected in all locations initially compared to simulated historic yields (Table 1), with gains starting to level off by mid-century, and then declining although to levels still above early-twenty-first-century yields, except at St. John that shows a greater decline. Lind is an exception, not declining if at all until the end of the century. The projected decline results from the combination of continued warming and a reduction in the rate of increase of CO_2 fertilization benefits. For winter wheat under RCP 4.5, yield increases are smaller due to a lower CO_2 fertilization effect, leveling off by mid-century but showing no subsequent decline (CO_2 fertilization compensating the more modest warming in this scenario). For spring wheat under RCP 8.5, yields at Moscow Mt. and Pullman showed trends similar to those of winter

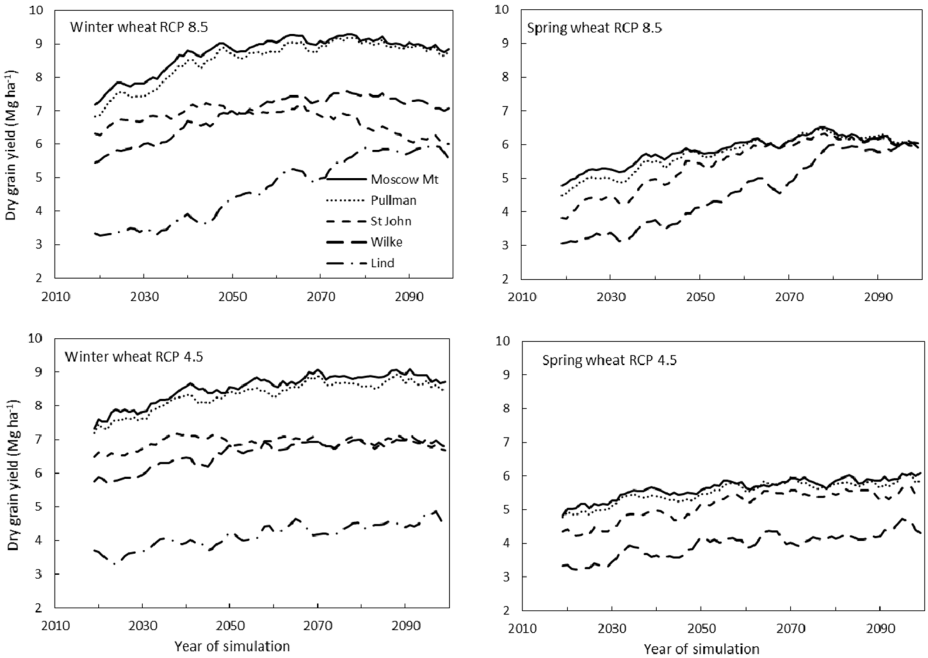

Fig. 3 Projected dry grain yields (5-year running averages) of winter and spring wheat for the period 2019 to 2100 under RCP 4.5 and RCP 8.5 climate projection scenarios under dryland conditions at five locations in the Inland Pacific Northwest. The simulation includes both climate change and CO_2 effects. See Table 1 for simulated historic wheat yields

wheat. At the drier St. John and Wilke sites, with fallow 1 out of 3 years, spring wheat yields following winter wheat were initially lower than at higher precipitation locations, but equaled the wetter sites by the end of the century due to higher soil water resulting from lower transpiration of winter wheat crops (Fig. 5). Under RCP 4.5, projected spring wheat yields increased slowly but steadily to the end of the century. This positive outlook for wheat grown in cooler high-latitude areas has been reported in other studies (Wilcox and Makowski 2014).

Figure 4 shows the response of simulated WW yield to growing season temperature, annual precipitation, and atmospheric CO_2 under RCP8.5 from 2019 to 2099 at the highest (Moscow Mt.), lowest (Lind), and intermediate (St. John) precipitation sites. Panels in the left column show that as temperature decreases, precipitation increases. While growing season temperature will increase by over 30% by the end of the century, precipitation will increase by about 12%. The result of this large temperature increase in light of a moderate increase in rainfall is that, at all sites, maximum yield will occur before the end of the century (Fig. 4, left column). Atmospheric CO_2 will increase by nearly 125% by 2099 under RCP 8.5. This CO_2 increase helps to increase yield to about mid-century at all sites, but beyond mid-century further increases in yield in response to CO_2 are stymied by shorter growing seasons imposed by higher temperatures, and a decrease of the response to CO_2 as concentrations approach photosynthetic CO_2 saturation.

3.4 Climate change and soil-crop water relations

Projected ET, crop transpiration (T), and transpiration-use efficiency (TUE) are influenced by the interaction between climate-change environmental conditions and soil-crop water relations

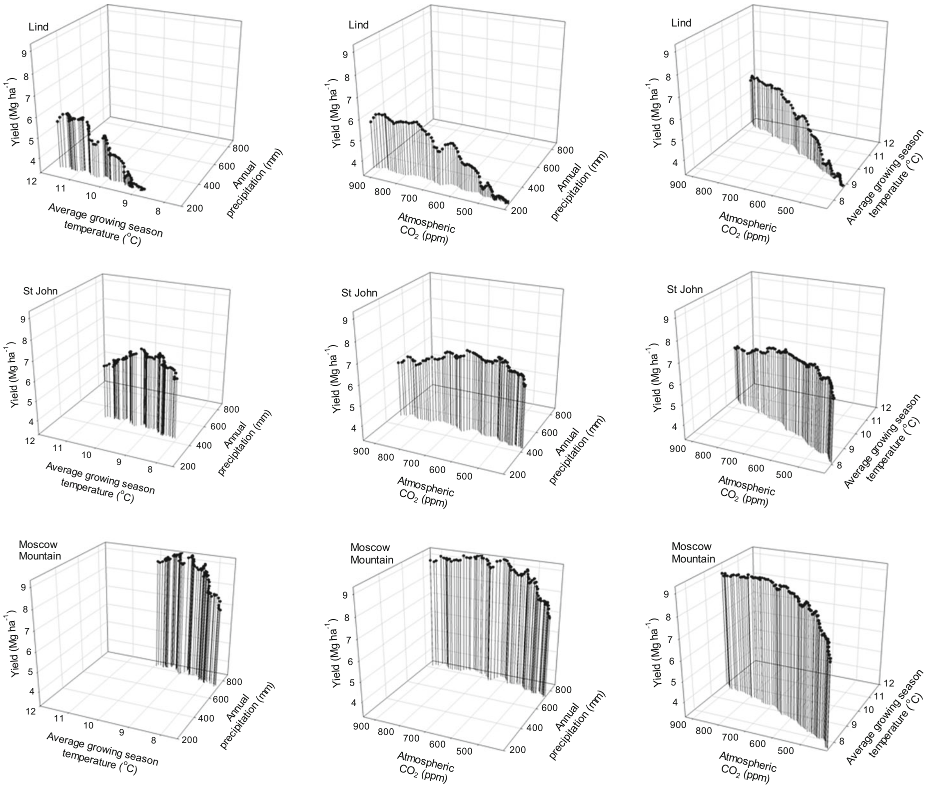

Fig. 4 Response of simulated dryland winter wheat dry grain yield to average growing season temperature, annual precipitation, and atmospheric CO_2 concentration at three locations in the Inland Pacific Northwest. Data are 5-year running averages from 2019 to 2099 for RCP 8.5. In all panels, time increases from *right* to *left*

(Fig. 5, examples under RCP 8.5). For winter wheat, ET remained unchanged until ~2040 and then declined at all locations except Lind which showed a slight increase. By the end of the century, ET was reduced below historic levels by about 115 mm at Moscow Mt. and Pullman, 155 mm at St. John, and by about 75 mm at Wilke. At the driest site (Lind), there was a slight upward trend in ET by midcentury reaching ~30 mm above historic levels. Trends were similar for spring wheat, but with smaller decline only apparent after 2070, and ET was overall about 25% lower than for winter wheat. Transpiration trends showed similar patterns to ET, but of course with lower water losses. Late in the century, spring wheat transpiration at Wilke was similar than that of the other sites (Fig. 5). For both winter and spring wheat, there was a dramatic TUE increase through the century, with the slope of change greater for winter wheat.

3.5 Winter versus spring crops under climate change in the PNW

Table 2 shows the ratio of future to historical yields, averaged for three periods. For winter wheat, the largest ratios are for Lind, the driest site with the greatest [CO_2] benefit, with ratios reaching ~1.4 and 1.9 by the end of the century for RCP 4.5 and RCP 8.5, respectively. Wilke, the second driest site, had ratios stabilizing around 1.2 by midcentury. In St. John, there was a small initial yield ratio increase, declining by the end of the century to 0.9 for RCP 8.5. The high precipitation

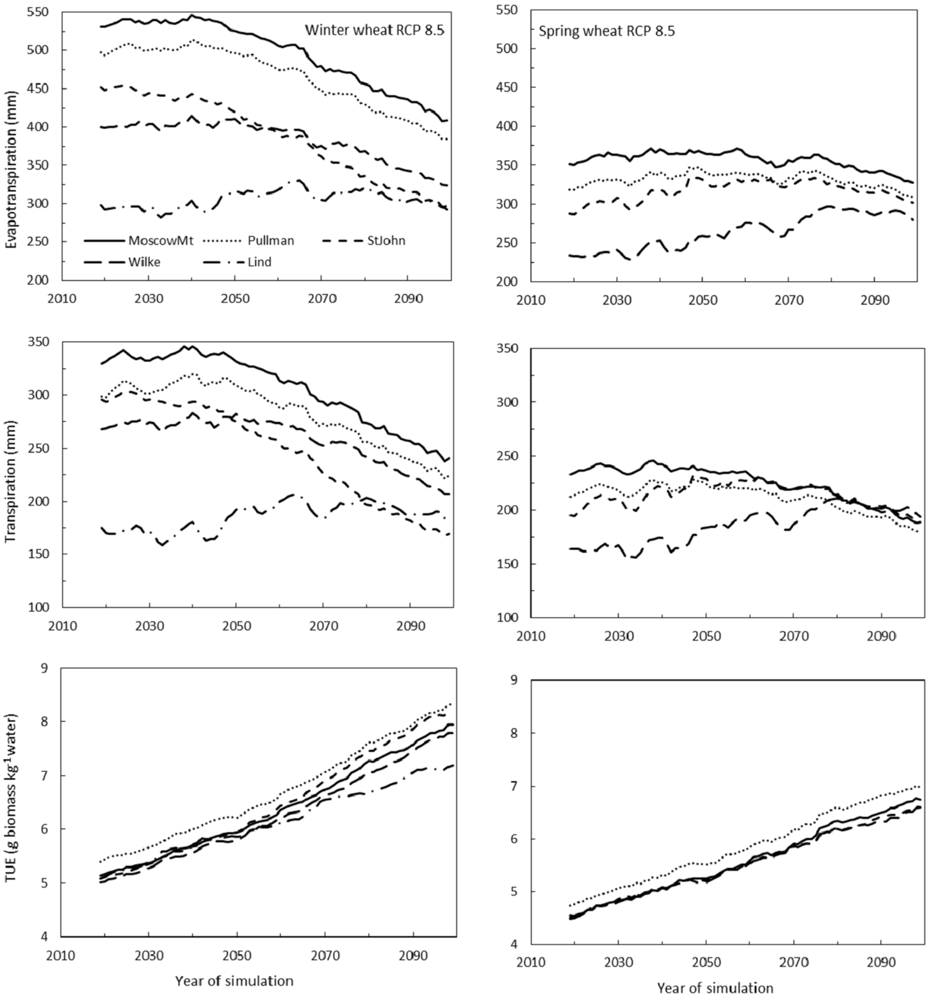

Fig. 5 Projected (5-year running averages) evapotranspiration, transpiration, and transpiration-use efficiency (TUE) for the period 2019 to 2100 under RCP 8.5 for winter and spring wheat under dryland conditions at five locations in the Inland Pacific Northwest

sites initially achieved ratios of ~1.12, stabilizing at ~1.2 for the next 60 years of the century. Regarding the range of projections, except for Lind (the highest mean ratios), the lower limit of the range included ratios below 1.0, especially late in the century while the higher limit reached values up to 1.5, indicative of the uncertainty in climate projections.

Projected yield gains for spring wheat were above 1 in all cases, greatest at Wilke and smaller for other sites as their annual precipitation increased, indicative of the greater CO_2 fertilization effect in drier conditions. Spring wheat yield ratio gains were higher than those of winter wheat in intermediate precipitation sites, but similar in sites with higher precipitation, suggesting the possibility of substitution in the future, i.e., greater adoption of winter wheat (greater yields than spring wheat) in these sites. This advantage of fall-seeded crops at the higher precipitation sites may extend to crops such as winter peas and canola. If so, intensification and diversification of

Table 2 Ratio of future to historic yields of winter wheat (WW) and spring wheat (SW) simulated for baseline rotations at five locations of the Pacific Northwest projected for two Representative Concentration Pathway (RCP) scenarios (4.5 and 8.5)

Location	Period	RCP	WW yield ratio	WW minimum ratio	WW maximum ratio	SW yield ratio	SW minimum ratio	SW maximum ratio
Lind	2010–2039	4.5	1.22	1.12	1.38			
		8.5	1.15	1.01	1.31			
	2040–2069	4.5	1.35	1.20	1.48			
		8.5	1.48	1.19	1.74			
	2070–2099	4.5	1.44	1.29	1.73			
		8.5	1.85	1.65	2.13			
Wilke	2010–2039	4.5	1.11	1.03	1.17	1.15	1.05	1.28
		8.5	1.09	1.00	1.15	1.08	0.97	1.17
	2040–2069	4.5	1.19	1.09	1.25	1.25	1.10	1.38
		8.5	1.22	1.06	1.35	1.32	1.02	1.55
	2070–2099	4.5	1.20	1.02	1.37	1.30	1.11	1.58
		8.5	1.22	1.00	1.53	1.63	1.46	1.71
St. John	2010–2039	4.5	1.04	0.95	1.12	1.18	1.10	1.28
		8.5	1.02	0.88	1.10	1.12	1.04	1.22
	2040–2069	4.5	1.03	0.93	1.17	1.30	1.16	1.42
		8.5	1.02	0.83	1.21	1.35	1.11	1.53
	2070–2099	4.5	1.00	0.83	1.20	1.34	1.11	1.63
		8.5	0.89	0.65	1.14	1.40	1.03	1.68
Pullman	2010–2039	4.5	1.14	1.07	1.21	1.14	1.04	1.26
		8.5	1.11	1.04	1.18	1.10	1.04	1.20
	2040–2069	4.5	1.21	1.14	1.28	1.21	1.06	1.31
		8.5	1.22	1.08	1.33	1.23	1.01	1.40
	2070–2099	4.5	1.22	1.04	1.40	1.23	0.99	1.47
		8.5	1.21	0.97	1.47	1.24	0.97	1.46
Moscow Mt.	2010–2039	4.5	1.12	1.05	1.22	1.11	1.00	1.27
		8.5	1.11	1.02	1.19	1.09	0.98	1.23
	2040–2069	4.5	1.19	1.13	1.28	1.16	0.98	1.26
		8.5	1.21	1.05	1.33	1.17	0.95	1.31
	2070–2099	4.5	1.20	1.02	1.36	1.18	0.95	1.36
		8.5	1.18	0.96	1.43	1.17	0.93	1.39

Ratios are averaged over 12 global climate models, among which the minimum and maximum ratios are presented for the respective crops

production in these locations could include various rotations with an emphasis on fall-planted crops.

3.6 Intensification and diversification of cropping systems

Alternative rotations (Table 1) include winter pea, greater use of winter wheat, and elimination of summer fallow, which can contribute to diversification and intensification through the reduction of time that the land is fallow. One measure of potential benefit derived from diversification is the ratio of total crop yield under the alternative rotation to total yield under the traditional rotation. If the ratio is greater than one, the alternative rotation is the higher yielding. This ratio, calculated for each year of the simulation, differs strongly among locations (Table 3). In the higher precipitation region, moving to a rotation having only winter crops consistently produced a higher total yield (yield ratios from 1.3 to 1.4) over the traditional 3-year rotation with two spring crops. The projected increase in annual precipitation (Fig. 1) and the reduction in ET (Fig. 5) explain some of the success of the alternative rotation in the annual cropping AEC, but we must also credit winter crops that outyield spring crops.

In contrast to the higher precipitation sites, the modeled alternative rotations at St. John and Wilke generally yielded less than the traditional ones (Table 3). The SW-SP-WW alternative rotation at St. John produced average total yield ratios close to one or above, so this alternative rotation may be a viable option at the wetter sites in the annual crop/fallow transition AEC, depending on economics—there would be a cost associated with raising the additional crop. The alternative rotations at Wilke and the SF-WW-WP at St. John performed poorly compared to the traditional rotation.

Table 3 Ratio of total grain yield from the alternative rotation to the total grain yield from the baseline rotation at four locations of the Pacific Northwest projected for two Representative Concentration Pathway (RCP) scenarios

Location	Alternative rotation	Period	RCP	Alternative/traditional yield ratio	Minimum ratio	Maximum ratio
Wilke	SF-WW-WP	2010–2039	4.5	0.94	0.91	0.97
			8.5	0.95	0.91	0.98
		2040–2069	4.5	0.94	0.90	0.96
			8.5	0.94	0.89	1.00
		2070–2099	4.5	0.94	0.91	0.98
			8.5	0.92	0.89	0.95
	SW-SP-WW	2010–2039	4.5	0.93	0.89	0.97
			8.5	0.91	0.88	0.95
		2040–2069	4.5	0.92	0.88	0.98
			8.5	0.91	0.83	0.99
		2070–2099	4.5	0.91	0.84	0.97
			8.5	0.98	0.91	1.10
St. John	SF-WW-WP	2010–2039	4.5	0.92	0.87	0.96
			8.5	0.93	0.88	0.96
		2040–2069	4.5	0.92	0.88	0.96
			8.5	0.92	0.88	0.97
		2070–2099	4.5	0.91	0.89	0.96
			8.5	0.93	0.90	0.97
	SW-SP-WW	2010–2039	4.5	0.98	0.92	1.01
			8.5	0.95	0.85	1.02
		2040–2069	4.5	1.00	0.91	1.05
			8.5	1.01	0.89	1.09
		2070–2099	4.5	1.01	0.88	1.09
			8.5	1.12	1.03	1.19
Pullman	WW-WW-WP	2010–2039	4.5	1.29	1.24	1.37
			8.5	1.29	1.24	1.38
		2040–2069	4.5	1.32	1.28	1.38
			8.5	1.34	1.29	1.41
		2070–2099	4.5	1.33	1.29	1.38
			8.5	1.39	1.33	1.48
Moscow Mt.	WW-WW-WP	2010–2039	4.5	1.32	1.26	1.38
			8.5	1.32	1.28	1.41
		2040–2069	4.5	1.34	1.30	1.42
			8.5	1.36	1.32	1.44
		2070–2099	4.5	1.34	1.30	1.41
			8.5	1.39	1.34	1.47

The ratio was calculated on an annual basis and averaged over 12 global climate models for which the minimum and maximum ratios are presented. Rotation designations as in Table 1

In summary, simulated intensification of the farming systems worked well in the annual cropping AEC, but was marginal at best in the lower-precipitation, annual crop/fallow transition AEC.

3.7 Other factors to consider

Factors not considered in this simulation study could certainly influence the outcome of the projections. Additional crops could be considered such as canola (both spring- and fall-planted cultivars). Canola has several potential benefits including nutrient recovery from the soil (Pan et al. 2016), facilitation of weed control (Esser and Hennings 2012), and biofuel production (Sowers and Pan 2013).

Climate change effects on insect pests were not considered. With warming, insect generation times will be shortened, with the potential to exacerbate pest damage to crops. Milder winter temperatures are likely to reduce overwinter kill, increasing insect pressure during the crop season. CropSyst did not account for insect pests.

Weeds respond to the weather much as do crops, so if crop biomass increases with climate change, weed biomass is likely to increase as well. Higher biomass accumulation in weeds translates to greater competitiveness. Also, new weed species will migrate into the region with climate change, and the competitive ability of particular weed species will change (Scott et al. 2014). CropSyst does not simulate weed pressure.

Heterogeneity of the physical and economic conditions in the region exceed those considered in this study. As the sites analyzed here show, there is substantial heterogeneity within, as well as between, the major cropping systems that cannot be fully represented through a small number of sites. Future research should combine spatially explicit crop model simulations at a larger number of sites with economic analysis that incorporates physical and economic heterogeneity due to differences in farm size and economic conditions. Preliminary economic analysis of cropping system adaptations in the region shows that these physical and economic factors, as well as environmental policy, all influence the viability of cropping system adaptations (Antle et al. 2016). For example, large crop insurance subsidies on grain crops and not on winter legume crops could affect the economic returns to the types of rotations discussed here.

4 Conclusions

Projections of future climate in the IPNW include significant annual and seasonal temperature increases at all locations and some precipitation increases, more so in high precipitation locations. Higher winter and spring temperatures will benefit the growth of winter crops and would allow for earlier planting of spring crops, with earlier maturity of both type of crops allowing avoidance of the more extreme summer heat. Considering only climate change effects (no [CO_2] effects), yields were projected to be preserved throughout the century for RCP 4.5 but increased first and then declined to levels equal or below initial values for RCP 8.5, except for Lind which showed some gain. Trends were similar for winter and spring crops. When [CO_2] effects were included, wheat yields for RCP 8.5 were projected to increase up to mid-century and then decline to levels generally above initial values by the end of the century. Wheat yields for RCP 4.5 showed a smaller increase, but steady until the end of the century. Future to baseline winter wheat yield ratios were greater than one at all sites, but much higher for the driest site. For spring wheat, relative yield gains decreased steadily from drier to wetter sites. Crop water use of winter wheat is projected to decrease significantly in all locations except Lind, although winter wheat will utilize more water than spring wheat. For this reason, although diversification of cropping systems by partial replacement of winter wheat with other winter crops such as winter peas and canola should be feasible, depending on economics, replacing spring with winter crops in current rotations appears only feasible in high precipitation locations of the IPNW.

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References

Abatzoglou JT (2013) Development of gridded surface meteorological data for ecological applications and modelling. Int J Climatol 33:121–131. doi:10.1002/joc.3413

Abatzoglou JT, Brown TJ (2012) A comparison of statistical downscaling methods suited for wildfire applications. Int J Climatol 32:772–780. doi:10.1002/joc.2312

Ainsworth EA, Rogers A (2007) The response of photosynthesis and stomatal conductance to rising [CO_2]: mechanisms and environmental interactions. Plant Cell Environ 30:258–270

Allen LH (1990) Plant responses to rising carbon dioxide and potential interactions with air pollutants. J Environ Qual 19:15–34

Antle JM, Stöckle CO, Mu J, Zhang H, Abatzoglou J. (2016) Methods to assess dryland wheat cropping system adaptations to climate change. Agric Ecosyst Environ, submitted.

Asseng S, Ewert F, Martre P et al (2015) Rising temperatures reduce global wheat production. Nat Clim Chang 5: 143–147

Bocchiola D, Nana E, Soncini A (2013) Impact of climate change scenarios on crop yield and water footprint of maize in the Po valley of Italy. Agr Water Manage 116:50–61

Chaudhuri UN, Kirkham MB, Kanemasu ET (1990) Carbon dioxide and water level effects on yield and water use of winter wheat. Agron J 82:637–641

Chen C, Miller P, Muehlbauer F, Neill K, Wichman D, McPhee K (2006) Winter pea and lentil response to seeding date and micro- and macro-environments. Agron J 98:1655–1663

Cleland EE, Chuine I, Menzel A, Mooney HA, Schwartz MD (2007) Shifting plant phenology in response to global change. Trends Ecol Evol 22:357–365

Esser A, Hennings R (2012) Winter canola feasibility in rotation with winter wheat. Washington State University Extension Fact Sheet FS068E.

Ferris R, Ellis RH, Wheeler TR, Hadley P (1998) Effect of high temperature stress at anthesis on grain yield and biomass of field-grown crops of wheat. Ann Bot-London 82:631–639

Grant RF, Wall GW, Kimball BA, Frumau KFA, Pinter PJ Jr, Hunsaker DJ, Lamorte RL (1999) Crop water relations under different CO_2 and irrigation: testing of *ecosys* with the free air CO_2 enrichment (FACE) experiment. Agric For Meteorol 95:27–51

Huggins D, Pan B, Schillinger W, Young F, Machado S, Painter K (2015) Crop diversity and intensity in Pacific Northwest dryland cropping systems. In Regional Approaches to Climate Change for Pacific Northwest Agriculture–Climate Science Northwest Farmers Can Use. REACCH annual report, year 4, www.reacchpna.org.

Huggins DR, Pan WL (1991) Wheat stubble management affects growth, survival, and yield of winter grain legumes. Soil Sci Soc Am J 55:823–829

Kimball BA, LaMorte RL, Pinter PJ, Wall GW, Hunsaker DJ, Adamsen FJ, Leavitt SW, Thompson TL, Matthias AD, Brooks TJ (1999) Free-air CO_2 enrichment and soil nitrogen effects on energy balance and evapotranspiration of wheat. Water Resour Res 35:1179–1190

Long SP, Ainsworth EA, Rogers A, Ort DR (2004) Rising atmospheric carbon dioxide: plants FACE the future. Annu Rev Plant Biol 55:591–628

Manderscheid R, Weigel HJ (2007) Drought stress effects on wheat are mitigated by atmospheric CO_2 enrichment. Agron Sustain Dev 27:79–87
McGee R, Pfaff J, Guy S, Chen C (2014) Developing food quality autumn-sown legumes. http://css.wsu.edu/biofuels/files/2014/02/McGee2014OSDS.pdf. Accessed 28 July 2016.
Pan WL, McClellan Maaz T, Hammac WA, McCracken VA, Koenig RT (2016) Mitscherlich-modeled, semi-arid canola nitrogen requirements influenced by soil nitrogen and water. Agron J 108:1–11
Papendick RI (1996) Farming systems and conservation needs in the Northwest wheat region. Am J Alternative Agr 11:52–57
Parker LE, Abatzoglou JT (2016) Projected changes in cold hardiness zones and suitable overwinter ranges of perennial crops over the United States. Environ Res Lett 11(3):034001
Reuveni J, Bugbee A (1997) Very high CO_2 reduces photosynthesis, dark respiration, and yield in wheat. Ann Bot-London 80:539–546
Riahi K, Rao S, Krey V, Cho C, Chirkov V, Fischer G, Kindermann G, Nakicenovic N, Rafaj P (2011) RCP 8.5—a scenario of comparatively high greenhouse gas emissions. Clim Chang 109:33–57
Rupp DE, Abatzoglou JT, Hegewisch KC, Mote PW (2013) Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA. J Geophys Res-Atmos 118(10):884–810. doi:10.1002/jgrd.50843
Schillinger, W.F., Papendick, R.I., Guy, S.O., Rasmussen, P.E., Van Kessel, C. (2006). Dryland Cropping in the Western United States. Chapter 11, Dryland. Agriculture, 2nd ed. Agonomy Monograph No. 23, ASA/CSSA/SSSA, Madison, WI.
Scott JK, Webber BL, Murphy H, Ota N, Driticos DJ, Loechel B (2014) Weeds and climate change: supporting weed management adaptation. AdaptNRM, http://adaptnrm.csiro.au/wp-content/uploads/2014/08/Adapt-NRM_M2_WeedsTechGuide_5.1_LR.pdf. Accessed 30 July 2016.
Siebert S, Ewert F, Rezaei EE, Kage H, Graβ R (2014) Impact of heat stress on crop yield—on the importance of considering canopy temperature. Environ Res Lett 9:044012
Sommer R, Glazirina M, Yuldashev T et al (2013) Impact of climate change on wheat productivity in Central Asia. Agric Ecosys Environ 178:78–99
Sowers KE, Pan WL (2013) Washington oilseed cropping systems project. Part of the Washington State biofuels initiative. 2013 annual progress report. http://css.wsu.edu/biofuels/files/2012/09/2013-Biofuel-Cropping-Systems-Research-Progress-Report.pdf. Accessed 30 July 2016.
Stöckle CO, Donatelli M, Nelson R (2003) Crop Syst, a cropping systems simulation model. Eur J Agron 18:289–307
Stöckle C, Kemanian A, Nelson R, Adam JC, Sommer R, Carlson B (2014) Crop Syst model evolution: from field to regional to global scales and from research to decision support systems. Environ Model Softw 62:361–369
Stöckle CO, Nelson RL, Higgins S, Brunner J, Grove G, Boydston R, Whiting M, Kruger C (2010) Assessment of climate change impact on eastern Washington agriculture. Clim Chang 102:77–102
Thomson AM, Calvin KV, Smith SJ, Kyle GP, Volke A, Patel P, Delgado-Arias S, Bond-Lamberty B, Wise MA, Clarke LE, Edmonds JA (2011) RCP 4.5: a pathway for stabilization of radiative forcing by 2100. Clim Chang 109:77–94
Tubiello FN, Rosenzweig C, Kimball BA, Pinter PJ, Wall GW, Hunsaker DJ, LaMorte RL, Garcia RL (1999) Testing CERES-wheat with free-air carbon dioxide enrichment (FACE) experiment data: CO_2 and water interactions. Agron J 91:247–255
Wilcox J, Makowski D (2014) A meta-analysis of the predicted effects of climate change on wheat yields using simulation studies. Field Crops Res 156:180–190