Impacts of potato and maize management and climate change on groundwater recharge across the Central Sands

Final Report to the Wisconsin Department of Natural Resources

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Introduction

Irrigated agricultural land use expansion and surface water declines in the Wisconsin Central Sands (WCS) region

Irrigated agriculture profoundly changes the coupled water and energy cycle from field to global scales. Pumping groundwater to the soil surface increases crop evapotranspiration (ET), which is considered consumptive groundwater use because water is depleted from a specific time and place in an aquifer (Winter, 1999). Globally, 4500 km^3 of groundwater was depleted in the 20th century with agricultural demand for freshwater predicted to increase during the 21st century (Konikow, 2011). Regional stakeholders share groundwater as a common resource and the expansion of irrigated agriculture inevitably leads to community conflicts about water scarcity and equity.

The Wisconsin Central Sands (WCS, Fig. 1) irrigates 80,000 hectares of potato, maize, pea, and bean crops, which require over 335 billion liters of groundwater and comprise a $450 million agricultural and processing industry in the state of Wisconsin (NASS, 2013; Kraft, 2013; Keene and Mitchell, 2010). There are approximately140 family farms in the WCS, many of which survived Wisconsin's Dust Bowl to build profitable agribusinesses contingent on unrestricted groundwater access (Goc, 1990). Though irrigation is still considered supplemental in the Midwest, it has been compulsory in the WCS since it tripled yields from fast-draining, sandy soils in the 1950s (French and Lynch, 1957).

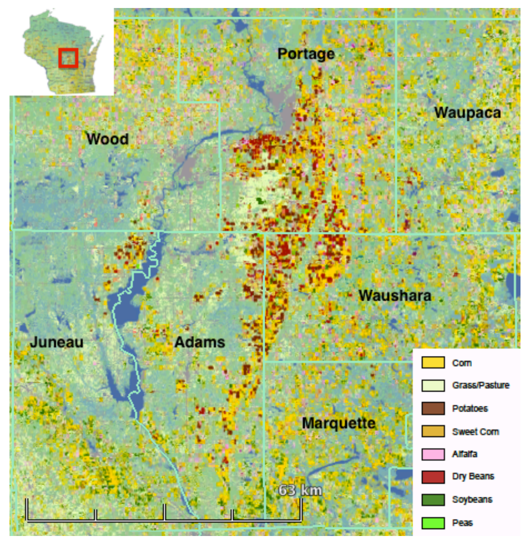


Figure 1. Wisconsin Central Sands location and prevalent crop types depicted by National Agricultural Statistics Service 2013 Cropland Data Layer.

Growers pump groundwater via high-capacity wells from an unconfined aquifer that replenishes 1000 km of headwater trout streams, 80 lakes, and extensive wetlands (Kraft et al. 2012; WI-DNR 2014). WCS residents and tourists prize these surface waters as ecosystems that support fishing, swimming, biodiversity, and spirituality. In the WCS, surface and groundwater are inextricably linked to one another, which directly ties the expansion of irrigated agriculture to the loss of aquatic ecosystem services. Prophetic hydrological studies in the late 1960s warned of future impacts to WCS surface waters if aquifer development for agriculture persisted, but these warnings went unheeded and the number of high-capacity wells in Wisconsin increased exponentially from less than 50 in

1960 to over 3800 in 2013 with the majority located in the WCS (Weeks et al. 1965; Weeks and Stangland, 1971; Smail, 2013).

In the late 2000s, hydrological predictions were actualized and many WCS surface waters began to exhibit severe stress and trout death (Kraft and Mechenich, 2010). These stresses include the drying of the Little Plover River in 2005-2009, which was named one of America's most endangered rivers in 2013 (American Rivers, 2013). The hydrologic stress, trout death, and continued irrigation expansion in the WCS fuel a 60-year old, litigious community conflict between aquatic and agricultural stakeholders over consumptive groundwater use and equity.

Present understanding and knowledge gaps of groundwater recharge, evapotranspiration, and climate in the WCS

Generally and in the WCS, consumptive groundwater use via crop evapotranspiration (ET) constitutes 70-85% of groundwater withdrawals for irrigation, while 15-30% of pumped groundwater may be recharged back into the aquifer (Weeks and Stangland, 1971; Winter, 1999). For the purpose of maintaining aquatic ecosystems, contemporary evidence suggests that consumptive groundwater use via crop ET is not recoverable. Pumping with high capacity wells shifts recharge patterns and exacerbates depletion in surface waters that depend on a critical zone of groundwater supplied from the first few meters of saturated aquifer thickness (Kraft et al. 2012; Condon and Maxwell, 2014). Irrigated crop ET is inferred to be of sufficient magnitude at 480-550 mm (WCS precipitation is 790-810 mm) to cause predicted and observed surface water depletion in the WCS (Weeks et al. 1965; Weeks and Stangland 1971; Tanner et al. 1974; Naber, 2011; Kraft et al. 2012; Kniffin et al. 2014) and there is enough existing information to begin equitable management of water resources. However, developing better management and policy requires an improved understanding of the spatiotemporal distribution of ET and "net" groundwater recharge (precipitation minus ET) from different irrigated cropping systems and how these relationships may be impacted by climate change (WCS Listening Sessions, 2011).

Though it is generally understood that irrigation increases cumulative annual crop ET and therefore decreases groundwater recharge by at least 50 mm, the spatiotemporal variability of ET and recharge from irrigated agroecosystems in the WCS remains uncertain. Spatially, differences in ET and recharge within a single irrigated field and crop type may be related to portions intrafield differences in topography, crop growth, and soil texture. Differences in daily ET between crop types on different fields within a close proximity to one another occurs because of crop growth, phenology, and agroecosystem management (e.g. residue and cover crop application). Characterizing these intrafield and intercropping system differences in ET and recharge from real agroecosystems in the WCS is critical to parameterize, calibrate, and validate process-based models of ET and groundwater recharge.

Process-based agroecosystem models of ET and net groundwater recharge such as Agro-IBIS (Kucharik, 2003) explicitly incorporate physiological and biophysical mechanisms taking place in the soil-plant-atmospheric based on causal relationships that may be continually tested in the field. Empirical models of potential or reference ET extrapolate correlative relationships between meteorological variables and crop physiology developed and validated for a particular site without explicit representation of soil-plant-atmospheric mechanisms. In the absence of site-specific crop or biophysical data, potential or reference ET models (e.g. Allen et al. 1998, Priestley-Taylor 1972, Hargreaves-Samani 1982) often serve as useful indices of overall evaporative demand and irrigation scheduling tools. Though approximating ET and net recharge using potential or reference ET and crop coefficient approaches may provide initial estimates for the WCS, these empirical models are unsuitable for analyzing differences between irrigated cropping systems or predicting how ET and recharge from these systems may respond to multidecadal climate change, interannual climate variability, or the implementation of water sustainability measures. Though the data requirements, field-tested causal relationships, and parameters are robust; a process-based agroecosystem model of ET and net groundwater recharge is required for resilient, comprehensive management of water resources in the WCS in the face of a changing climate.

Goals of the Research

The overarching goal of this project was to quantify on-farm crop ET and net recharge for dominant crop rotations in the WCS with greater spatial and temporal resolution than previous endeavors to test causal relationships and collect physiological and biophysical parameters required for building a process-based agroecosystem model of ET and net recharge for the WCS (Agro-IBIS, Kucharik, 2003).

The specific objectives were to (1) Utilize new vadose zone instrumentation and other biophysical field measurements in potato and maize cropping systems to quantify groundwater recharge under these crop types, and understand hydrogeological responses associated with crop type, irrigation, tillage, and cover crops; (2) Utilize field measurements to develop, parameterize, and validate potato and maize crop functional types in the Agro-IBIS agroecosystem model to link groundwater recharge to aboveground processes by capturing coupled carbon-water energy exchange; (3) Drive Agro-IBIS using a new, high resolution (8km x 8km) historical daily climate dataset (1948-2010) and varied land management scenarios (e.g. irrigation, crop/vegetation type, tillage) to understand how cumulative changes in climate and land management have impacted groundwater recharge and evapotranspiration in Wisconsin Central Sands over the past 60 years.

Methods

Isherwood Farms Field study

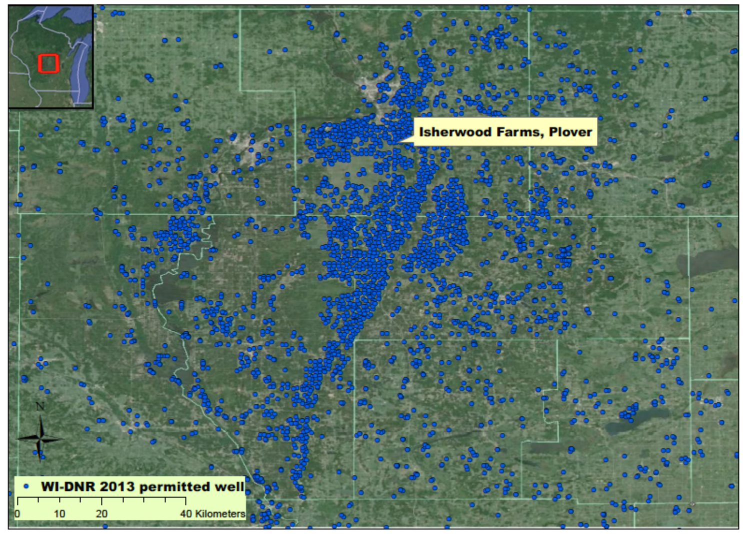


Figure 2. Isherwood Farms, Plover, WI with permitted 2013 high-capacity wells in the Wisconsin Central Sands

Because our goal was to conduct field measurements under realistic agricultural cultivation in the WCS, we collaborated with Isherwood Farms, a 600-hectare, sixth generation family farm with 100 acres of woodland and 7 km of stream edge in Plover, WI (Fig. 2). Isherwood farms greatly assisted us in the installation of permanent vadose zone instrumentation on six of the farm's agricultural fields and freely shares cultivation practices and agronomic data with our research group. We intend to extend this collaboration past the duration of this project to collect long-term data on Isherwood Farms.

Vadose zone lysimetry and soil environmental conditions

Monolithic lysimeters have been the benchmark that validates all other water budget methods and models because the physical flux of water can be captured from them as drainage with ET as the remaining balance of the water budget (Farahani et al. 2007). Accurate partitioning between crop ET and potential recharge from different cropping systems in the WCS was a fundamental goal of this project. The most accurate lysimeters available to measure this partitioning are equilibrium tension lysimeters (Brye et al. 1999; Brye et al. 2000; Masarik et al. 2004), which have a transient lower boundary condition that automatically adjusts itself to match adjacent soil water potential, but these are cost-prohibitive and require regular in-field maintenance, which relegates them to field edges.

Lysimeters for this study needed to be low-maintenance and sturdy enough that they could be replicated, installed in the center of agricultural fields, and regularly have industrial agricultural equipment operate over them. Passive capillary lysimeters use a constant head lower boundary condition maintained by a hanging water column created from a fiberglass wick (Gee et al. 2002; Gee et al. 2003, Fig. 3). This constant head boundary can cause flux convergence or divergence if surrounding soil is at a higher or lower head than the lysimeter and drainage flux rates are very low. However, at modeled drainage fluxes between 1-10,000 mm, passive capillary lysimeters having a 0.6 m wick and a 0.6 m soil column had 100% collection efficiency in sand (Gee et al. 2009). Additionally, a 2.5 year comparison of between passive capillary and large weighing lysimeters in sandy soils in Germany found cumulative drainage to have less than 5% variability between lysimeter types with drainage timing and flux rate also being comparable (Gee et al. 2009). These considerations, paired with the coarse soils and humid climate in the WCS and their relative sturdiness, make passive capillary lysimeters an ideal choice for measuring ET and drainage in the WCS.

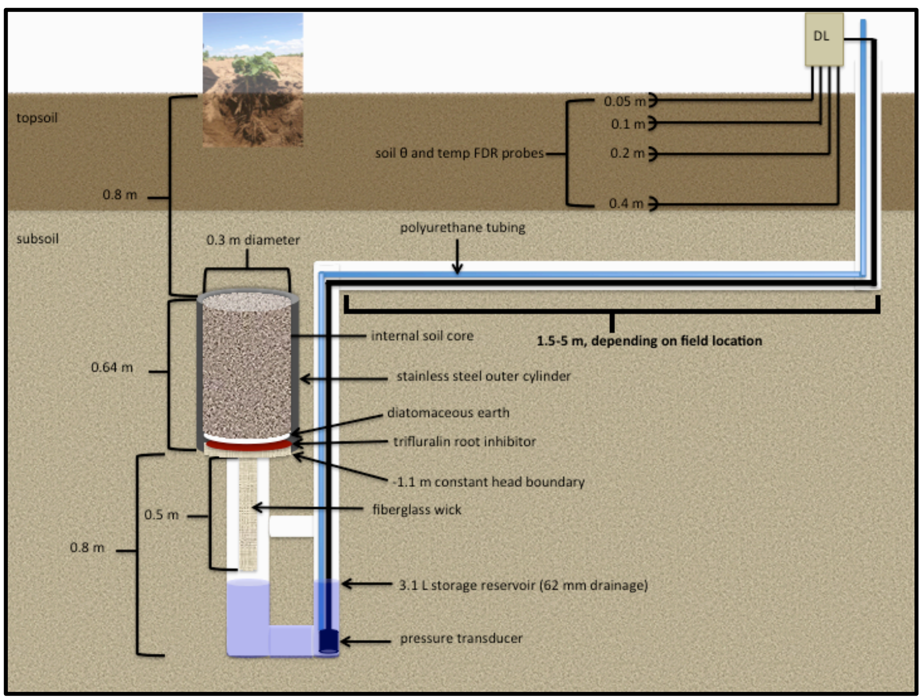
We installed 24 passive capillary lysimeters newly designed to capture up to 5-minute flux rates using pressure transducers (Drain Gauge G3, Decagon Devices, Inc; Fig. 3, top) on 6 fields at Isherwood Farms in 2013 and 2 additional lysimeters in a field with limited central coverage (an existing lysimeter was not in a consistently planted area of the field). We installed lysimeters deep enough so that the depth of drainage collection (1.4 m) would be below the maximum effective rooting depth for vegetable crops in the Wisconsin, which is estimated at 0.5 m for potato, 0.6 m for sweet corn and peas, and 1.2 m for field corn (Curwen and Massie, 1994), though surface irrigation and root system plasticity lead to maximum effective rooting depth for maize in irrigated systems being less than 0.8 m (Coelho and Or, 1999; Phene et al. 1991; Isherwood, 2013, personal communication).

A 0.5 m diameter auger was used to create cylindrical, vertical 2.2 m deep holes for lysimeters adjacent to 0.6 m trenches to transport tubing and wiring to the surface through PVC pipes (Fig. 3). Stainless steel cores were filled with monoliths from soil at a 0.8-1.4 m depth, at a distance of 6-8 meters from the installation hole. In order to preserve soil hydraulic properties, we took undisturbed soil monoliths to using a sledgehammer method for 16 lysimeters where soil structure was strong enough monoliths to remain intact during excavation. The remaining 8 soil monoliths did not remain completely intact when excavated from the extremely stony Rosholt soil series near the glacial moraine. Therefore, we excavated soil at 0.8-1.4 m into layers to carefully pack the remaining 8 soil monoliths (or portions of the monoliths that did not remain intact) to observed surrounding bulk density. Top and sub-surface horizons were separated and backfilled on top of lysimeters to approximate observed bulk density of surrounding soils.

Drainage may be estimated by the passive lysimeters in two ways: via pressure transducer measurements of water level in the storage reservoir (5-minute fluxes) or via pumping the drainage out through polyurethane tubing attached to the pressure transducer with a vacuum pump (weekly fluxes). At initial installation and during the 2014 field season, pressure transducer wires and polyurethane tubing were routed 5 m off the fields or at least 1.5 m away from the lysimeter to limit disturbance and allow easier accommodation of farm equipment (Fig. 3, top configuration). However, we observed that the pressure transducers were providing unreliable drainage estimates compared to the weekly measurements of pumped drainage. For this reason, we feel that the weekly pumped drainage data was more reliable than the pressure transducer data for the 2014 growing season. However, we also realized that without being able to check the polypropylene tubing each week, it had the potential to move up the lysimeter chamber and underestimate weekly fluxes. Based on all of these issues, we decided to reconfigure the experiment for the 2015 growing season.

Prior to the 2015 growing season, we conducted "surgeries" on the lysimeters by removing soil layers and excavating the 1.5-5 m PVC network that housed pressure transducer wiring and tubing. Because the drain gauges were newly designed with the vented pressure transducers at the time of installation, our study piloted their application in sandy soils under agricultural fields with cultivation occurring over them. We identified several key functional issues (i.e. water in the vents) with the pressure transducers and administered solutions (i.e. Teflon filters over the vents) in the spring of 2015 prior to planting. Our new lysimeter configuration (Fig. 3, bottom) allows us to ensure that the polypropylene tubing is at the bottom of the chamber each week and access the pressure transducer for maintenance whenever necessary. Additionally, we can ensure that we are pumping out all of the drainage each week by listening while we pump and if needed, looking into the reservoir. Because the pressure transducer zero can become unstable over time, we used our 2015 weekly pumping data to zero the transducers each week. Thus, we collected both 5-minute flux data and weekly pumped drainage for the 2015 growing season.

After testing the soil moisture variability of soil moisture and temperature at several depths in 2014, we decided to locate probes (5TM probes, Decagon Devices, Inc.) at 0.1, 0.1, 0.4, and 0.8 m depths near each lysimeter in an undisturbed portion of soil (Fig. 3, bottom). We will use a combination of drainage and interpolated soil moisture data to estimate daily ET for the 2015 growing season.



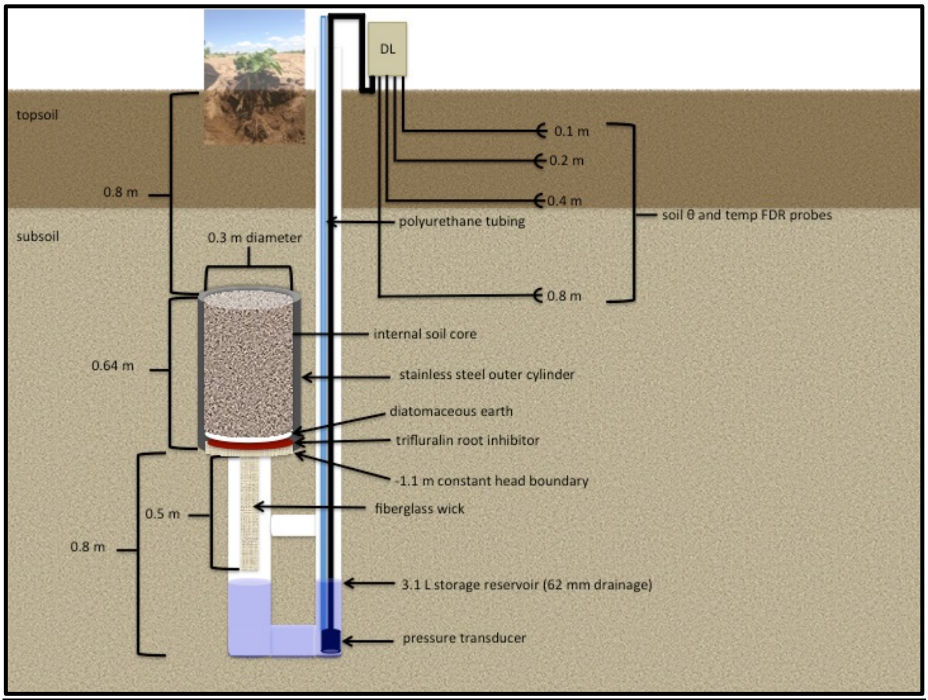


Figure 3. Lysimeter and soil moisture/temperature probe experimental design before (top) and after (bottom) 2015 reconfiguration for weekly access to pressure transducer and polypropylene tubing.

Micrometeorology

We collected temperature, relative humidity, total solar radiation, wind speed, and precipitation data by installing three meteorological stations (Hobo brand, Onset) adjacent to each of our fields.

Photosynthetic response to CO_2 and light

When building a robust process-based model of ET and net recharge, the most challenging input to contend with is the bulk stomatal conductance (or resistance) of the canopy (Kool et al. 2013), which involves scaling estimates of leaf area index (LAI) and stomatal conductance from leaf to canopy for the modeled time step. This scaling requires the creation of a canopy conductance submodel within the greater ET and net recharge model framework. We are developing models of stomatal conductance in both C3 (potato, pea) and C4 (maize) crops, which are derived from models of photosynthesis (Collatz et al. 1991, Collatz et al. 1992). These submodels will allow both crop photosynthesis and canopy conductance to physiologically respond to micrometeorological variables at a 5-minute time step in the greater Agro-IBIS framework.

In order to parameterize photosynthesis and canopy conductance submodels in potato, maize, and peas grown in the WCS, we collected gas exchange measurements from agricultural fields on Isherwood Farms over a 15°C temperature range between the hours of 09:00-17:00 Central Standard Time (when ET, photosynthesis, and stomatal conductance rates are the highest) during the 2015 growing season. We used a Li-Cor LI-6400 portable photosynthesis system equipped with a standard leaf chamber, and adjustable LED red/blue light source, and a CO_2 gas injection system. We measured fully expanded leaves from the top one-third of the canopy to capture their responses to intracellular CO_2 (A-ci curves). We are using 2015 A-ci curves to fit key photosynthetic parameters (table 1) required to model canopy conductance to our gas exchange data using a nonlinear least squares procedure for either C3 or C4 photosynthetic pathways. We have currently completed the fitting procedure for the C3 crops and are working to complete fitting for sweet corn, a C4 crop.

Plant phenology

We measured canopy leaf area index (LAI) (m^2 leaf area per m^2 ground area) approximately every 7-10 days in each instrumented field for 2013-2015 growing season. We took five measurements at 7-12 representative points per field each week using a Li-Cor LAI-2200c plant canopy analyzer (Li-Cor, Lincoln, Nebraska, U.S.A.). All measurements were collected under overcast sky conditions, clear skies (using the new scattering correction offered by the 2200c package after 2014), or at sunrise and sunset.

Agro-IBIS modeling

A key calibration/validation goal is to formulate logic that triggers irrigation events with realistic frequency and magnitude to match observed irrigation records and soil moisture profiles. We calibrated the model to generate realistic values for annual cumulative irrigation and individual irrigation events over the growing season and are working to calibrate irrigation frequency.

We typically conceptualize irrigated agriculture as increasing actual ET to values near potential ET by removing water as a limiting factor to transpiration. However, we hypothesize that potential ET or the evaporative demand of the landscape may also change as a result of conversion to irrigated agriculture. Irrigated agriculture may darken the soil (through increased water content) and change the reflectance and transmittance of individual leaves contributing to the canopy, which would change the surface albedo. In order to better understand how evaporative demand has changed in the WCS over the past 60 years in conjunction with actual ET (AET), we added empirical submodels of potential or reference ET (PET, RET) to Agro-IBIS. These submodels of PET and RET will also allow us to compare the performance of empirical models of ET and recharge (with crop coefficients) to the new process-based models of ET and recharge that we will build, validate, and calibrate using collected WCS data.

Specifically, we implemented Hargreaves-Samani (1985) PET, Priestley-Taylor (1972)

PET, and FAO-RET (Allen et al. 1998) into the Agro-IBIS modeling framework as submodels that receive actual or simulated inputs. Hargreaves-Samani PET represents the simplest index of evaporative demand, which is independent of land cover. Priestly-Taylor PET and FAO-RET represent more complex models of evaporative demand that change based on the land cover associated with each simulation. Using Agro-IBIS to estimate net shortwave radiation for Priestly-Taylor PET and RET models provides a unique opportunity to reconstruct land cover-specific evaporative demand without 60 years of gridded albedo values for the Midwest. Agro-IBIS calculates albedo throughout the growing season based on the fractional coverage of plants, soil, and snow that changes throughout the year. We updated the soil moisture-albedo response to an exponential model based on Somers et al. 2010 and Lobell and Asner, 2002. Agro-IBIS calculates net shortwave radiation on an hourly time-step based on incoming solar radiation and albedo. These net shortwave radiation values will be inputs to Priestley-Taylor PET and RET submodels.

Results

Final Project Status

Though we initially encountered some logistical, design, and functionality challenges implementing the new vadose zone instrumentation, we eventually were able to overcome them to collect 5-minute drainage (potential groundwater recharge) data for the 2015 growing season (cumulative 6/5/15-present) and weekly drainage data for the 2014 growing season (cumulative 11/10/2013-11/9/2014) from potato, sweet corn, field corn, and pea cropping systems at twenty-five sites in the WCS (Appendix 1). We have quantified cumulative water budgets for the fall 2013-2014 time period and plan to quantify daily water budgets for the growing and shoulder seasons beginning in 2015 and continuing for the foreseeable future. Additionally, we have successfully collected enough hydrological, micrometeorological, crop phenological, and crop physiological data from potato, sweet corn, field corn, and pea cropping systems to develop, parameterize, and validate processed-based models of ET and net recharge for potato, maize (field and sweet), and pea cropping systems.

Groundwater recharge from irrigated cropping systems

We used lysimetry, precipitation, and irrigation data to calculate annual water budgets for Nov. 10, 2013-Nov. 9, 2014 (Table 1). This time period was chosen based on the continuity of lysimetry data. The annual water budget is calculated using the water budget equation:

$P + I = R + ET$

In the annual budget, *P* is precipitation, which we measured adjacent to each field and supplemented with snow data from an NWS station 5 km from Isherwood farms. *I* is irrigation reported by the Isherwoods and validated by soil moisture data. *R* is annual potential recharge collected by lysimeters, which was physically pumped out and measured with a graduated cylinder on a weekly basis during the growing season (Fig. 4) and a monthly basis after a hard freeze (whenever equipment was not frozen). **Weekly potential recharge measurements include both precipitation and irrigation sources**. ET is the balance of this annual budget and the **net recharge is calculated as the difference between drainage and irrigation**. We assumed and verified that soil water storage was negligible at the annual time scale in these sandy soils.

Table 1. Cumulative water budgets from November 10, 2013 through November 9, 2014. All components of the water budget (Precipitation, Irrigation, Potential Recharge, Net Recharge) are reported in mm.

Cropping system (field name, soil subtype)	Precip	Irrigation	Potential recharge	Potential recharge CV	ET	ET CV	Net Recharge	Net Recharge CV
Potato (Gilman, Richford)	888	196	407	0.37	677	0.22	211	0.72
Peas-Pearl Millet (Homefield, Richford)	888	119	427	0.50	580	0.37	307	0.70
Sweet Corn (East Alt, Rosholt)	932	193	735	0.79	390	1.50	542	1.07
Sweet Corn (East Alt, Rosholt, without low outlier)	932	193	447	0.24	678	0.16	254	0.44
Sweet Corn (Louis, Richford)	927	142	486	0.79	583	0.66	343	1.11
Sweet Corn (Louis, Richford, without low outlier)	927	142	313	0.65	756	0.27	171	1.19
Field Corn (West Alt, Rosholt)	932	151	752	0.57	331	1.29	601	0.71
Field Corn (West Alt, Rosholt without low outlier)	932	151	556	0.64	567	0.40	405	0.52
Field Corn (Poznek, Richford)	927	169	530	0.65	565	0.61	362	0.95

Three lysimeters installed in relative topographical depressions on three different fields (sweet corn (Rosholt), sweet corn (Richford), and field corn (Rosholt)) acted as local recharge zones. These three lysimeters had significantly greater annual drainage than the sum of precipitation and irrigation, which results in a negative value of annual ET calculated using the above water budget. Therefore, we present water budgets for each field in Table 1 including and excluding these outliers.

The high variability present within agroecosystems in the cumulative water budgets can also be observed in weekly potential recharge patterns (Fig. 4). We observed high variability in the magnitude of drainage collected by lysimeters during larger precipitation events, which reflects localized recharge patterns at the subfield scale. Generally, this variability decreases along with the magnitude of drainage during times of high irrigation and low precipitation. During the warmest weeks of the summer, almost all of the irrigation and precipitation were consumed prior to reaching the drainage depth of the lysimeters (1.5 m). The locations of intrafield recharge zones appear to have remained persistent through the 2015 growing season, based on the preliminary potential recharge data presented for East Alt (sweet corn in 2014, potato in 2015) and Louis (sweet corn in both 2014 and 2015) in Fig. 2. Specifically, lysimeter 21 on East Alt and lysimeter 19 on Louis appear to be localized recharge zones for their respective fields in both 2014 and 2015.

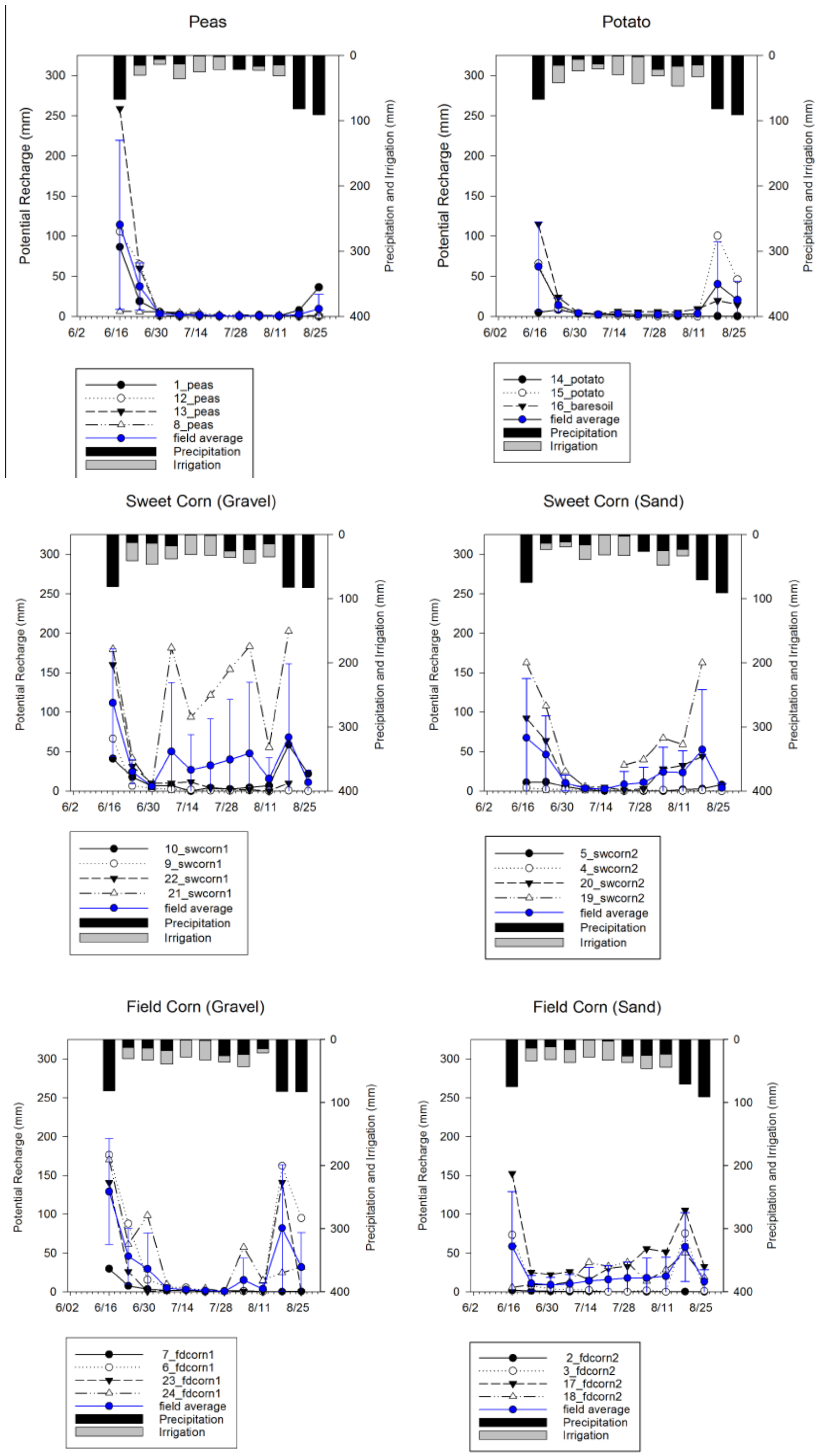


Figure 4. Weekly potential recharge measured by lysimeters (mm, left axes) along with precipitation and irrigation (mm, right axes) for six fields on Isherwood Farms during the 2014 growing season.

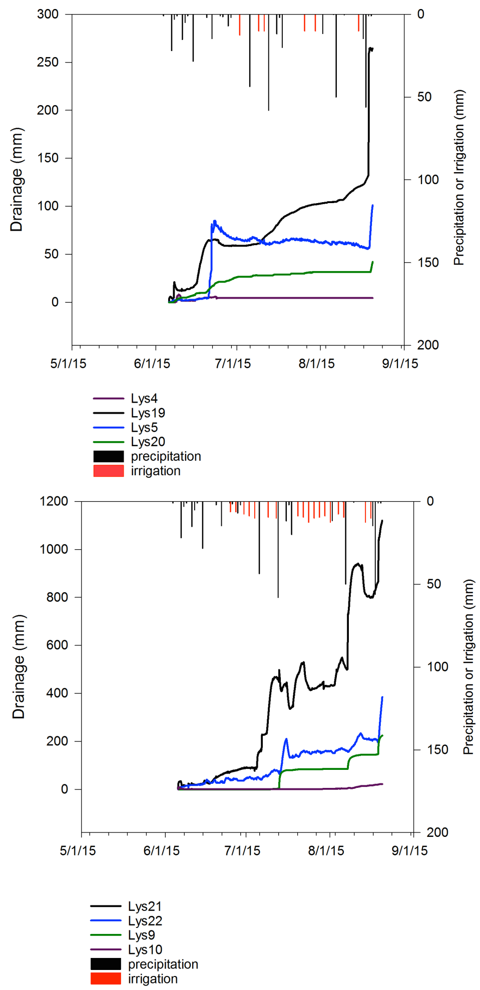


Figure 5. Potential recharge (mm, left axes, 5-minute flux from lysimeters) measured by pressure transducers during the 2015 growing season in sweet corn (top, Louis, sand) and potato (bottom, East Alt, gravel). Precipitation and irrigation (mm) are indicated by the right axes for each field.

Crop phenology from irrigated cropping systems

We observed differences in plant phenology across potato, sweet corn, field corn, and pea cropping systems, as evidenced by their leaf area index measurements in 2013 (Fig. 6) and 2014 (Fig. 7). Potato phenology reflects its growth and senescence prior to vine kill. Both sweet corn and field corn phenology reflect some senescence towards the end of their respective growing seasons, however there is a clear distinction between sweet and field corn phenology when the two are compared during the 2014 growing season (Fig. 7). To minimize variability, we increased the number of measurements taken each year from 5-7 measurements across each field in 2013, to 10 measurements across each field in 2014, to 12-14 spatially explicit measurements across each field in 2015.

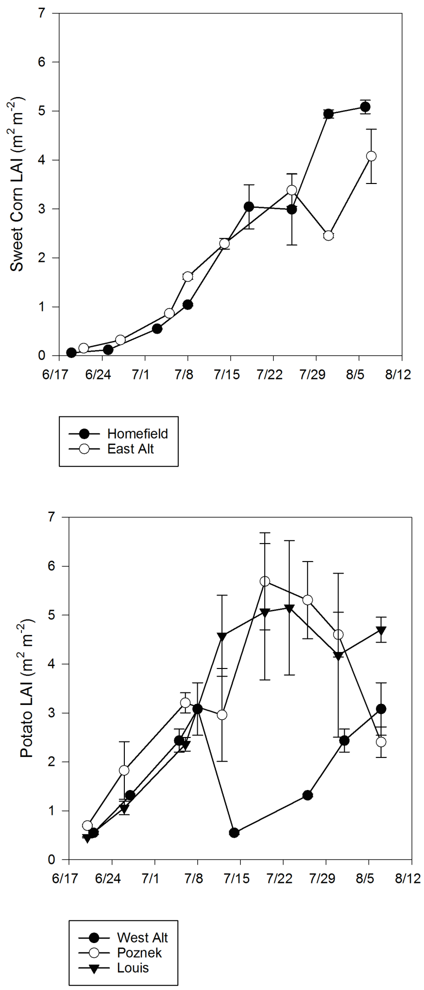


Figure 6. Leaf Area Index measured during 2013 growing season in sweet corn and potato from a total of five fields on Isherwood Farms.

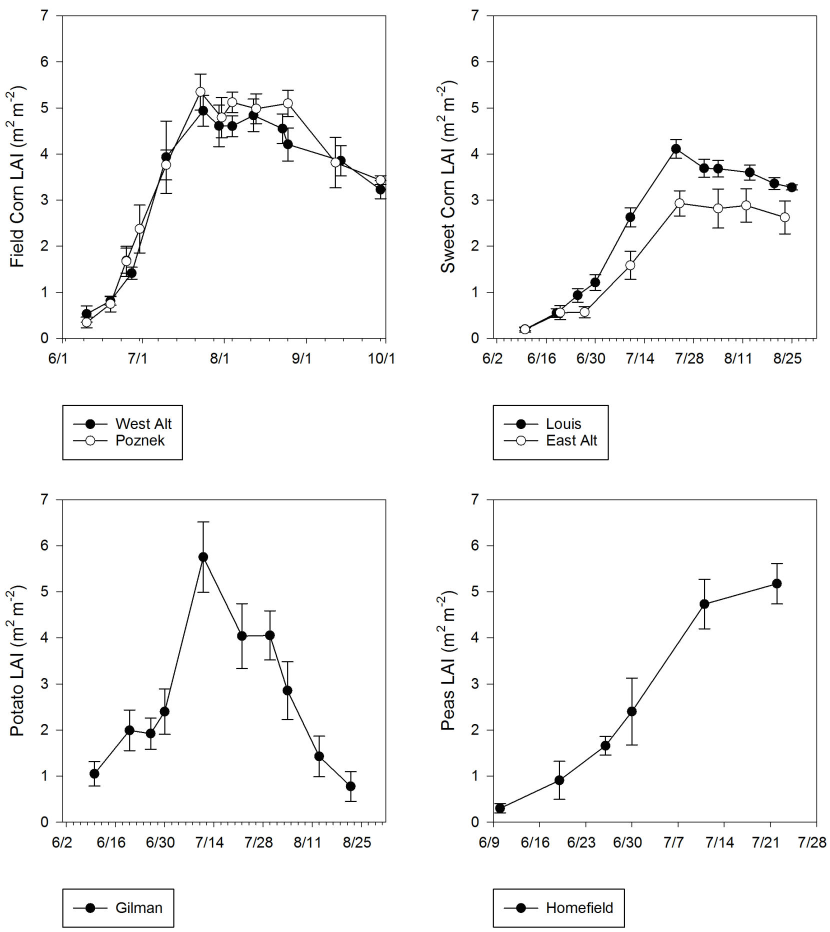


Figure 7. Leaf Area Index measured during 2014 growing season in field corn (top left), sweet corn (top right), potato (bottom left), and peas (bottom right) from six fields on Isherwood Farms in Plover, WI.

Soil moisture and temperature in irrigated cropping systems and implications for modeling

Parameters for modeling realistic irrigation events using soil moisture data

We observed that irrigation events typically maintain irrigated agroecosystems above field capacity (0.125 m^3 m^{-3} in the WCS). Though Isherwood Farms is widely acknowledged as a relatively low-input grower, soils typically do not drop below field capacity (Fig. 9) during the growing season. Agro-IBIS, along with most agroecosystem models, triggers irrigation events at 80-90% of maximum plant available water in the top 0.40 m of soil and irrigation is simulated by filling the soil profile to field capacity. For this reason, Agro-IBIS underirrigates maize in the WCS. We simulated irrigated Maize over Isherwood Farms between 1948-2007 and calculated mean annual irrigation during this time period to be 84 mm/yr, which is well below the average reported irrigation rate for maize in the WCS, which is 239 mm/yr (Smail, 2013). To realistically model irrigation events in the WCS to better fit field observations, we calibrated Agro-IBIS to trigger irrigation at 130% maximum plant available water in the top 0.40 m and irrigate to 200% of maximum plant available water (Fig. 10). This increases the mean annual irrigation between 1948-2007 over Isherwood Farms to 193 mm, which is still below though WCS average, but better approximates measured soil moisture data.

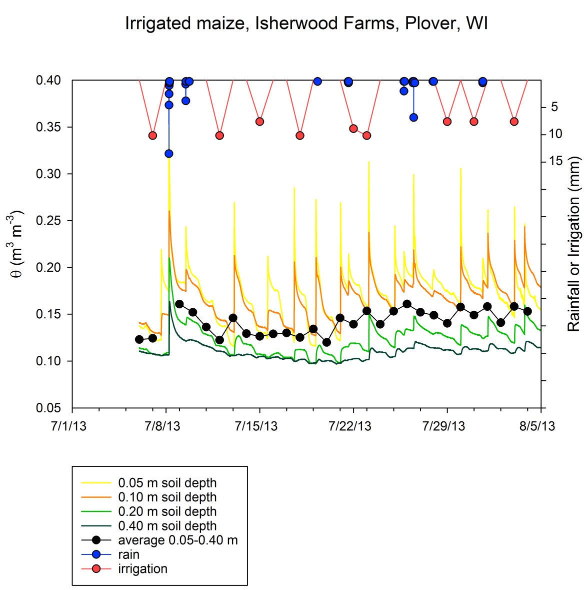


Figure 8. Soil moisture measured from several depths in an irrigated maize cropping system on Isherwood Farms during the 2013 growing season.

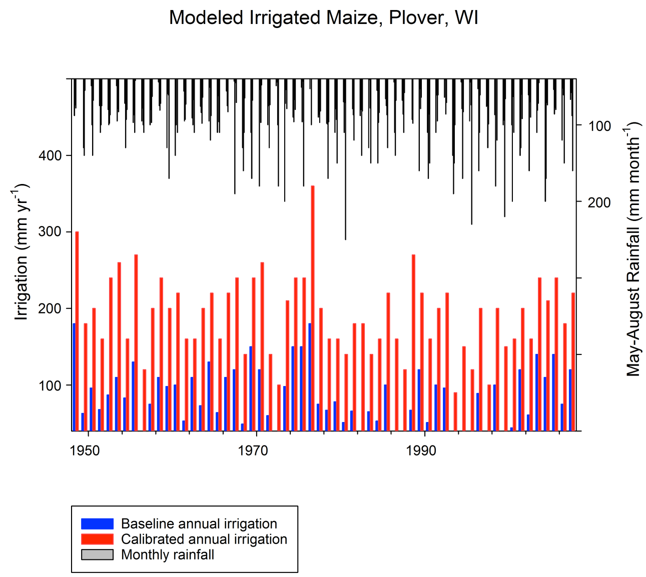


Figure 9. Baseline and calibrated annual irrigation rates for maize modeled over Isherwood Farms in Plover, WI between 1950-2007.

Seasonal soil cooling patterns from groundwater irrigation

Average groundwater temperature in the Central Sands has been reported as 9° C (Hennings and Connelly, 1980). We observed that irrigation with groundwater appears to prevent soil temperature from reaching its typical peak during the summer months (Fig. 8). These initial findings have implications for the way in which we model the soil energy balance in groundwater-irrigated agroecosystems, which is typically done in the Agro-IBIS model using Fourier approximations based on the seasonal pattern of soil temperature as curves that vary their amplitude and phase according to soil depth. Colder surface soil temperatures may also decrease evaporation from the soil surface. We plan to simulate this effect by altering the water temperature of irrigation events in the Agro-IBIS code.

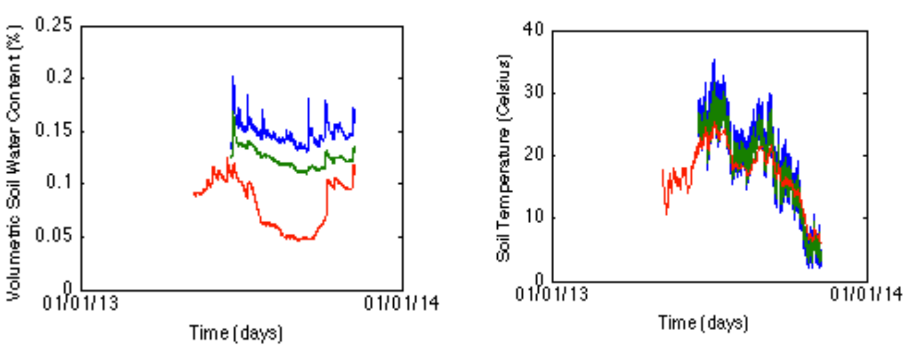


Figure 10. Soil moisture (left) and temperature (right) for 2013 growing season in irrigated maize treatment. Blue, green, and red lines represent soil moisture and temperature at 10, 20, and 40 cm depths, respectively.

Gas exchange and related model parameters from irrigated cropping systems

Three key parameters needed to build submodels of photosynthesis (and stomatal conductance) in the greater Agro-IBIS modeling framework are the maximal rate of carboxylation (Vcmax), dark respiration (Rd), and the light-saturated rate of electron transport (Jmax). Agro-IBIS calculates photosynthesis based on two key limitations: carboxylation rate by the enzyme RuBisCo (follows Michaelis-Menten kinetics) and the rate of electron transport, which is determined by light saturation. We used photosynthetic responses to CO_2 measured in the field (Appendix 2) to estimate these parameters using a nonlinear least squares curve fitting procedure for potato and peas across a broad range of leaf temperatures. We report the minimized sum of squared deviations as SSD for Vmax and Rd (fit together) and Jmax as well as all individual values in Appendix 3. Our estimates of these parameters are well within the range of what has been previously found for potato (Fleisher et al. 2012, Wullschleger, 1993) and peas (Farage and Long, 1995). The wide range of leaf temperatures that we captured during gas exchange measurements also allows us to characterize the temperature response of carboxylation (Fig. 11) in potato and pea, which can be used to further parameterize photosynthesis and canopy conductance in Agro-IBIS.

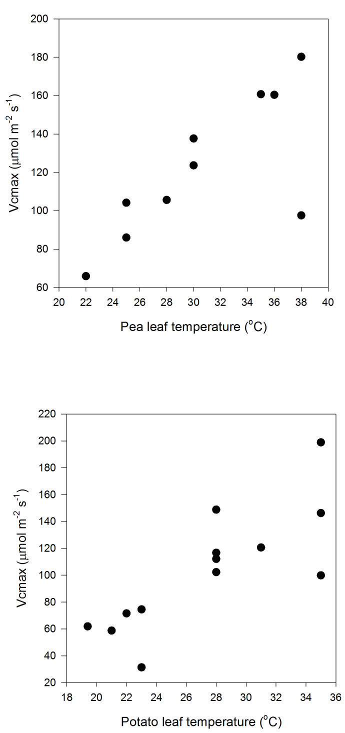
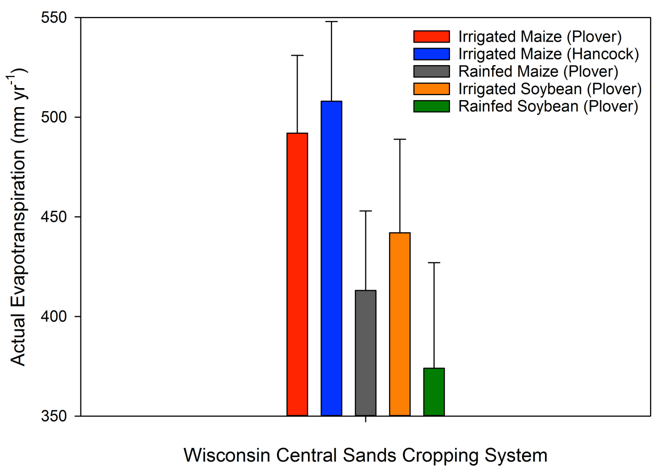


Figure 11. Temperature response of maximum carboxylation rate (Vcmax) in peas (top) and potato (bottom).

Potential evapotranspiration from irrigated vs. rainfed cropping systems

We successfully implemented Hargreaves-Samani (1985) PET, Priestley-Taylor (1972) PET, and FAO-RET (Allen et al. 1998) into the Agro-IBIS modeling framework. After implementation, we tested these new submodels in single-cell simulations over Isherwood Farms between 1948-2007 and have found preliminarily that both actual ET and the evaporative demand may change as a result of irrigation and changing surface albedo for both maize and soybean (used as a general C3 crop with phenology similar to potato) (Fig. 12). This changes the conceptual model of irrigated agroecosystems having actual ET rates at the potential ET of rainfed systems, as irrigation appears to also increase potential ET.



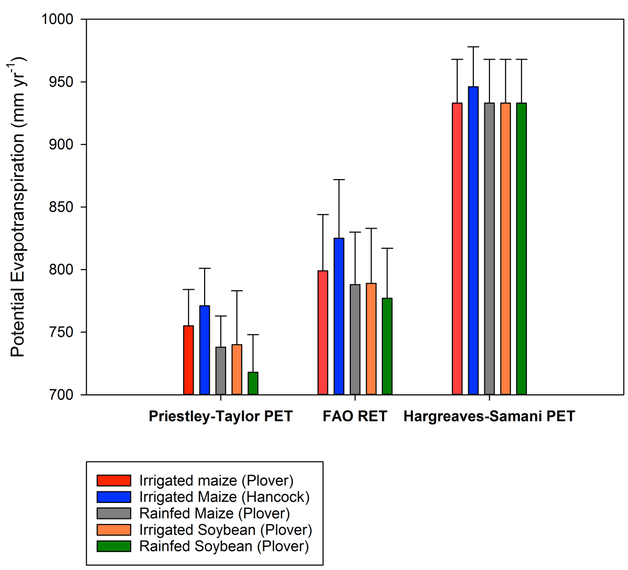


Figure 12. Modeled actual (top) and potential (bottom) annual evapotranspiration rates simulated by Agro-IBIS for 1948-2007

Conclusions and recommendations for future research

Spatiotemporal variability of groundwater recharge and evapotranspiration from WCS irrigated cropping systems

The observed variability of potential recharge from irrigated agroecosystems in the WCS may be the result of variability in topography, soil texture, soil hydraulic conductivity, local crop cover, or some combination of all of these variables. We plan to better understand this variability by mapping soil electrical conductivity and topography, and using these maps to sample for soil texture and plant phenology in 2015. From these data, we will be able to better understand how intrafield soil and topographical properties contribute to the variability in potential recharge and ET calculated from lysimeters. A future goal of this work will be to use intrafield measurements on hydrology, soil characteristics, and phenology to develop spatially-weighted, whole-field estimates of recharge and ET from irrigated cropping systems in the WCS.

Water budget modeling in the WCS

We have furthered our understanding of several biophysical mechanisms unique to irrigated agroecosystems in the WCS. We plan to use this increased mechanistic understanding, our robust field dataset, and site-specific physiological parameters to build process-based models of potential recharge and ET (Agro-IBIS) for potato, sweet corn, and pea functional types. By linking hydrology and carbon assimilation in these models, it will be possible to mechanistically explore the relationship between crop water use and crop productivity in the WCS. A future goal of this work will be to model regional solutions (i.e. precision irrigation, irrigation scheduling, deferred irrigation) over the WCS and assess their resilience to changes in climate.

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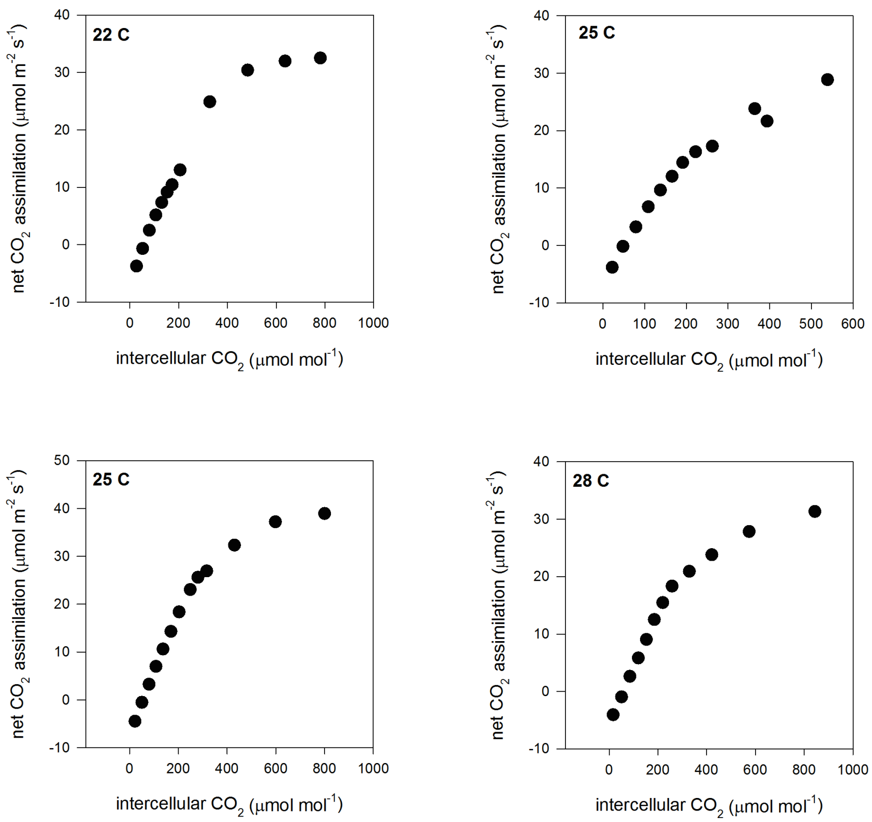
Appendix 1. Isherwood Farms Cropping Systems

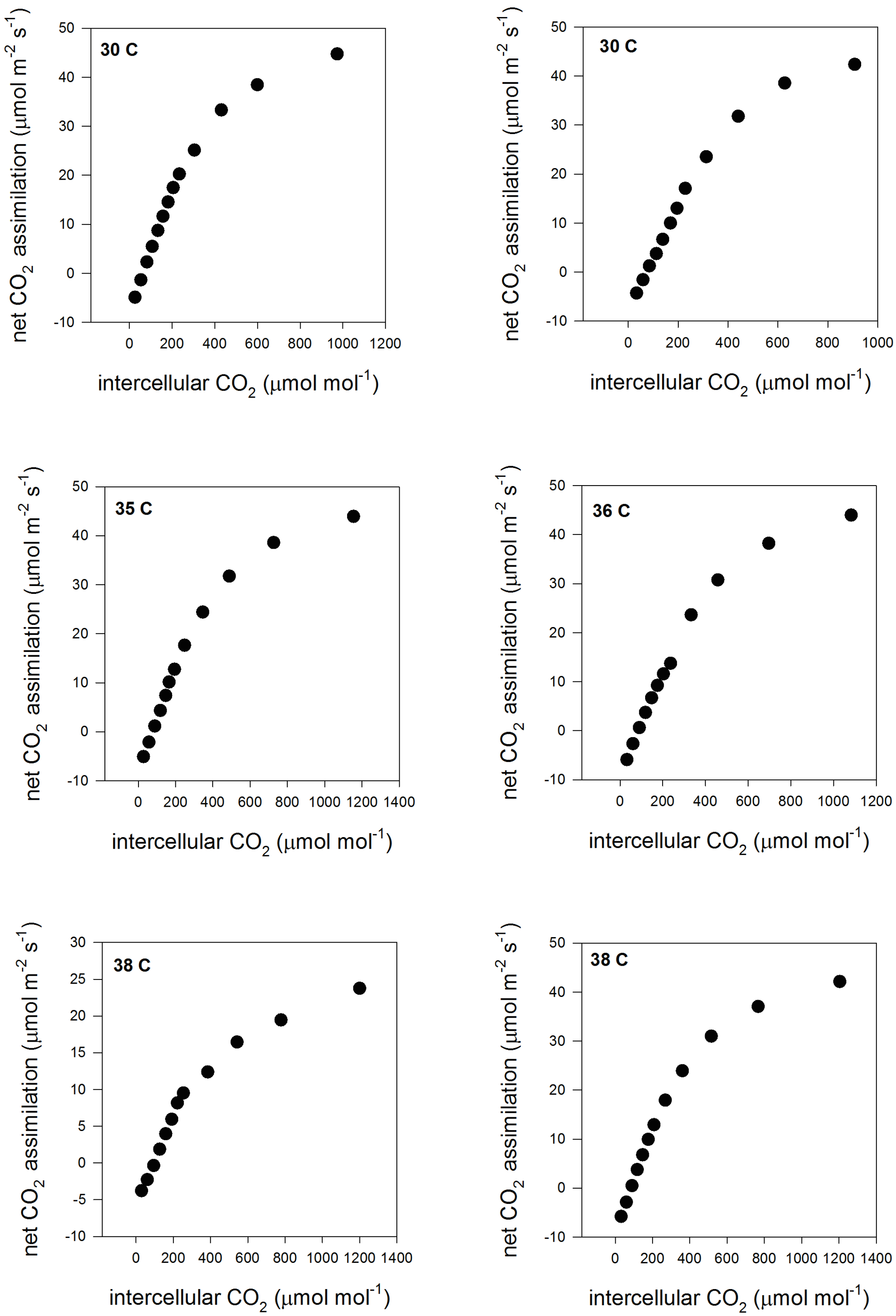
Cropping system name (# lysimeters)	Irrig.	Soil Series*	2014 seasonal changes in crop/soil cover				2015 seasonal changes in crop/soil cover			
			Spring	*Summer*	*Fall*	*Winter*	*Spring*	*Summer*	*Fall*	*Winter*
Poznek (4)	Irrigated	Richford	Field Corn	Field Corn	Field Corn	Maize Residue	Sweet Corn	Sweet Corn	Oat	Oat Residue
East Alt (4)	Irrigated	Rosholt	Field Corn	Field Corn	Field Corn	Maize Residue	Potato	Potato	Oat Residue	Oat Residue
Louis (4)	Irrigated	Richford	Sweet Corn	Sweet Corn	Oat	Oat Residue	Sweet Corn	Sweet Corn	Oat	Oat Residue
West Alt (4)	Irrigated	Rosholt	Sweet Corn	Sweet Corn	Oat	Oat Residue	Peas	Peas	Pearl Millet	Pearl Millet Residue
Gilman (3 +2 in 2015)	Irrigated	Richford	Potato	Potato	Oat	Oat Residue	Maize	Maize	Maize	Maize Residue
Homefield (4)	Irrigated	Rosholt	Peas	Peas	Pearl Millet	Pearl Millet Residue	Potato	Potato	Oat	Oat Residue

*Estimated from Otter and Fiala, 1978

Appendix 2. Photosynthetic response curves

Peas (C3 photosynthetic pathway)

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30 C
35 C
36 C
38 C
38 C
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intercellular CO2 (μmol mol-1)
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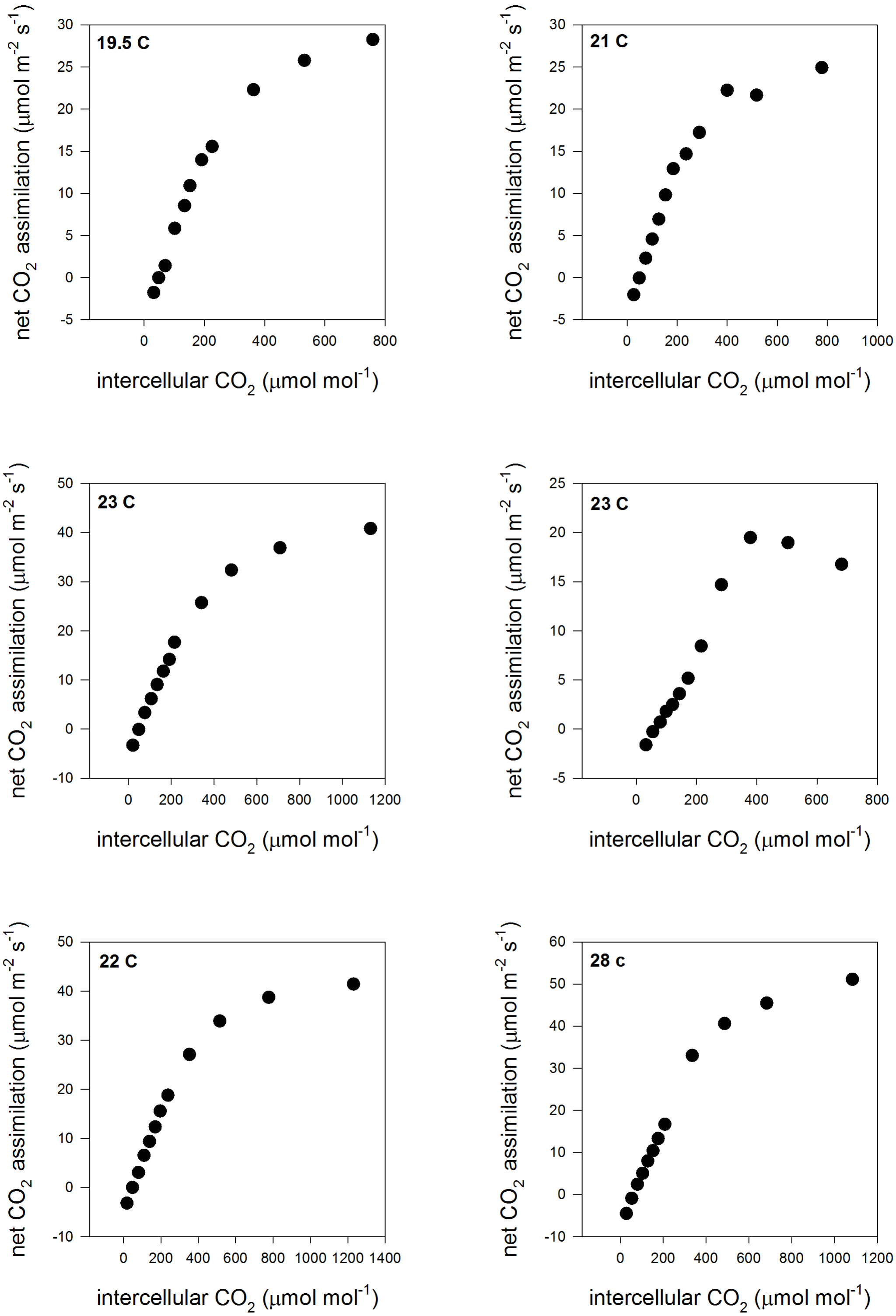
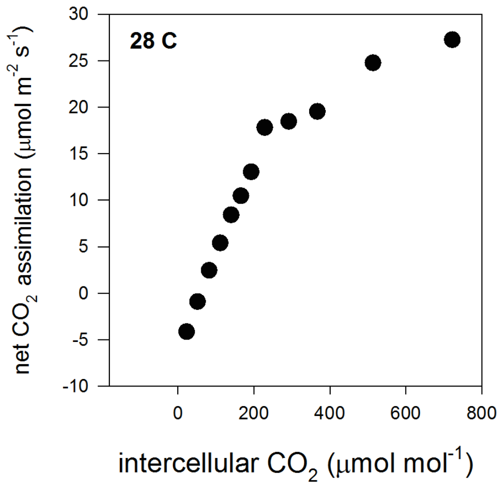
40
30
20
10
0
-10
0 200 400 600 800 1000 1200 1400
30
25
15
5
-5

Potato (C3 photosynthetic pathway)

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intercellular CO_2 (μmol mol^{-1})
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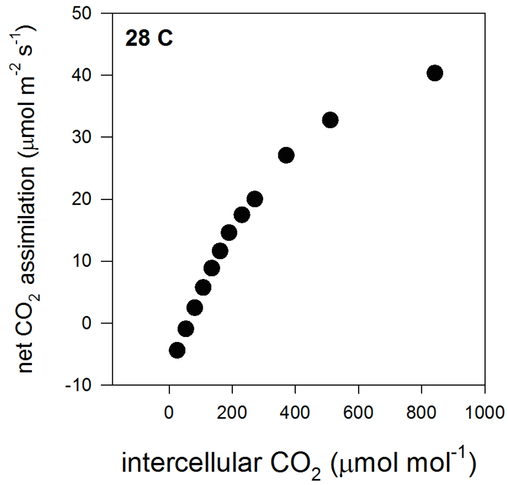
25
20
15
10
5
0
-5
-10
0
200
400
600
800


28 C
net CO_2 assimilation (μmol m^{-2} s^{-1})
intercellular CO_2 (μmol mol^{-1})
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40
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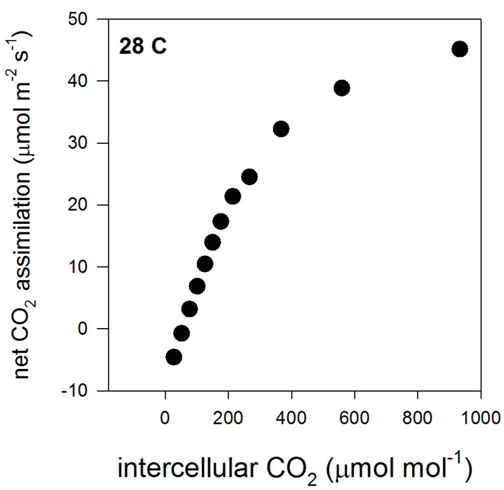
200
400
600
800
1000


28 C
net CO_2 assimilation (μmol m^{-2} s^{-1})
intercellular CO_2 (μmol mol^{-1})
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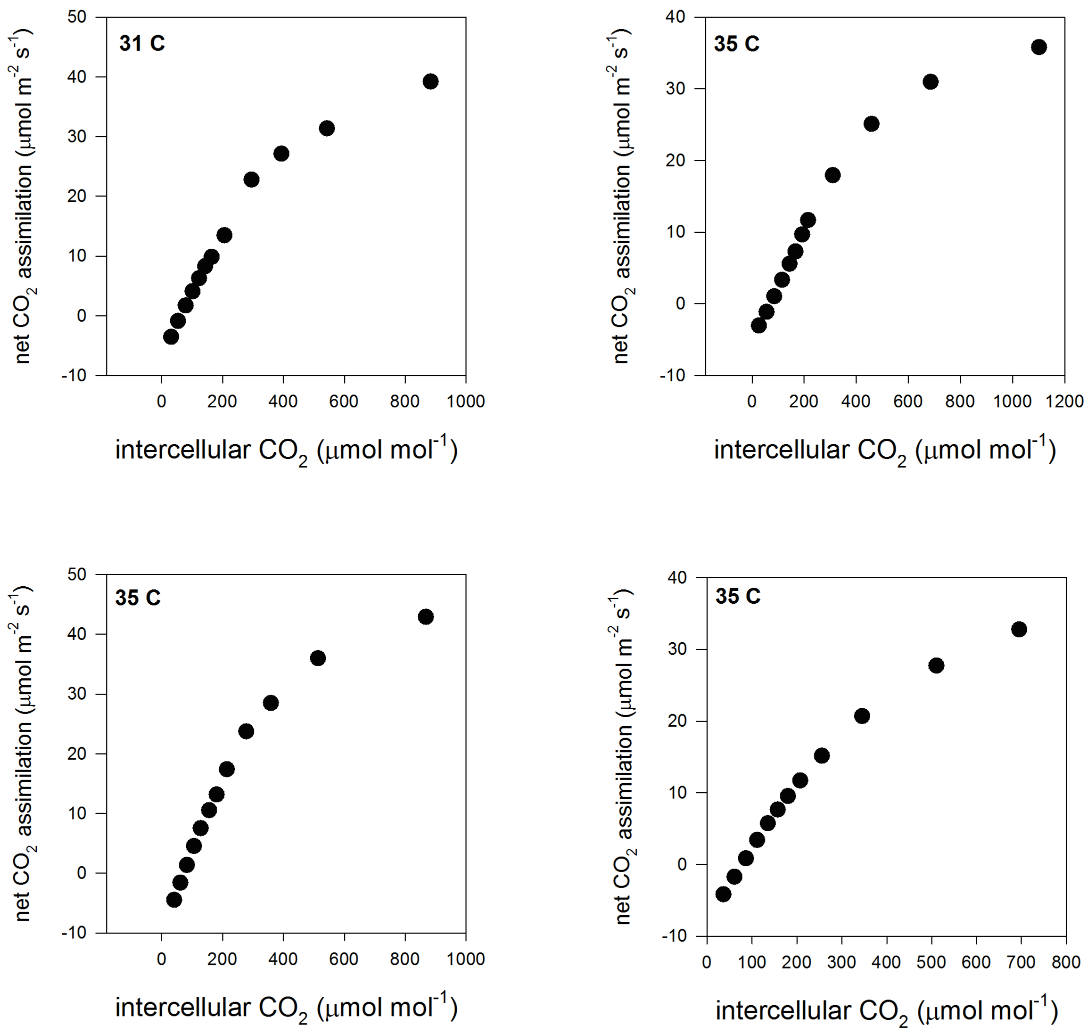
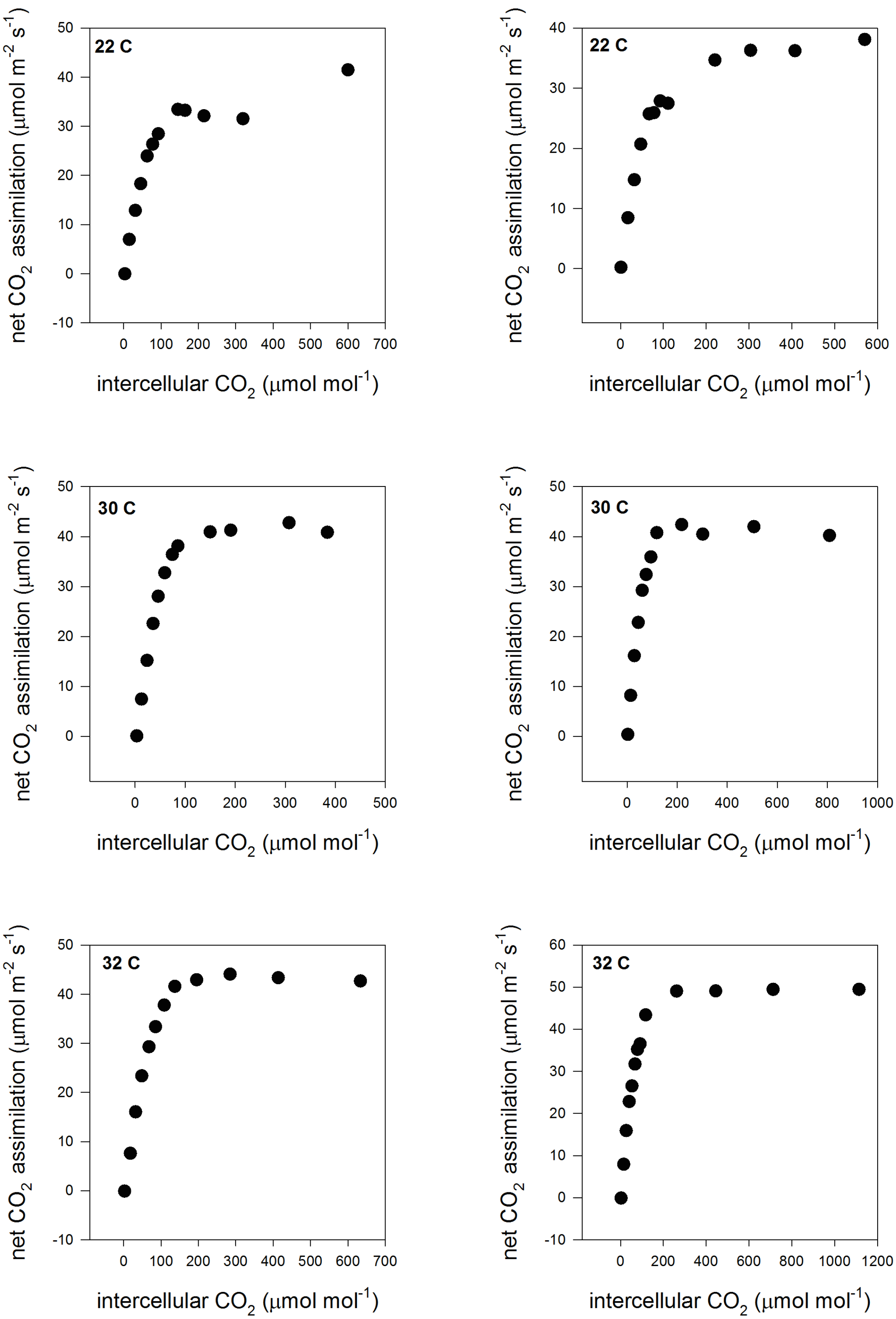
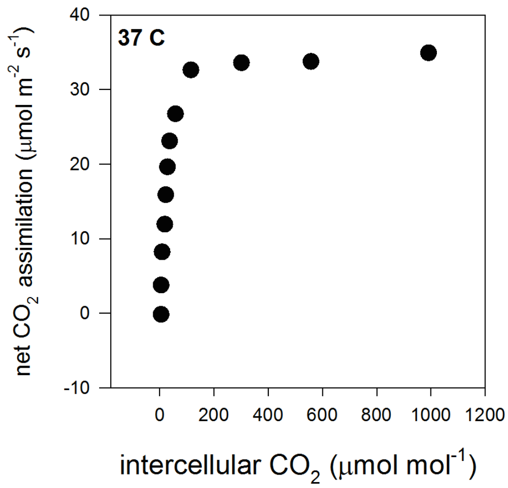
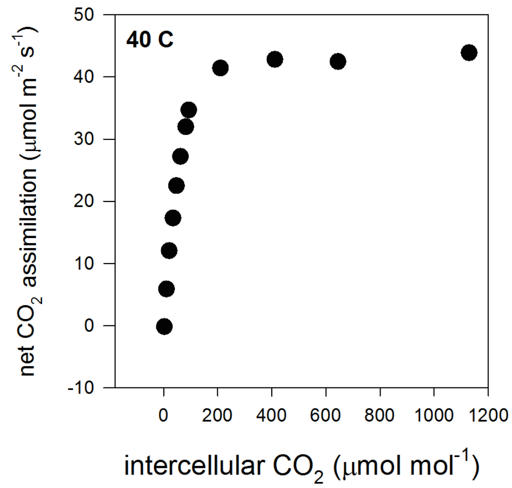

31 C
net CO2 assimilation (μmol m-2 s-1)
intercellular CO2 (μmol mol-1)
35 C
net CO2 assimilation (μmol m-2 s-1)
intercellular CO2 (μmol mol-1)
35 C
net CO2 assimilation (μmol m-2 s-1)
intercellular CO2 (μmol mol-1)
35 C
net CO2 assimilation (μmol m-2 s-1)
intercellular CO2 (μmol mol-1)

Sweet Corn (C4 photosynthetic pathway)







Appendix 3. Crop physiological parameters used in process-based models of photosynthesis and conductance

Crop	Temperature (Celsius)	Vcmax (umol m-2 s-1)	Rd (umol m-2 s-1)	Vcmax and Rd SSD	Jmax (umol m-2 s-1)	Jmax SSD
Potato	22	71.51	1.79	0.18	221.27	3.14
Potato	23	74.48	1.45	0.05	219.40	4.31
Potato	31	120.59	0.42	0.17	220.87	9.28
Potato	19.4	61.88	2.69	0.36	167.65	2.33
Potato	21	58.73	1.94	0.18	153.01	1.18
Potato	23	31.32	1.15	0.02	122.57	6.61
Potato	28	112.10	1.32	0.02	288.17	3.87
Potato	28	116.64	1.43	0.03	231.12	11.75
Potato	35	146.23	0.15	1.60	204.29	7.76
Potato	28	102.26	1.19	0.02	165.25	4.05
Potato	28	148.78	1.37	0.03	234.65	6.63
Potato	35	198.86	-0.12	0.76	260.73	3.76
Potato	35	99.83	-1.07	7.12	190.96	5.08
Peas	25	86.02	0.93	0.06	178.01	6.86
Peas	22	65.89	2.29	0.03	197.54	0.04
Peas	25	104.20	1.90	0.04	234.24	2.58
Peas	30	137.65	0.98	0.08	256.53	5.20
Peas	35	160.74	-0.23	5.61	245.01	4.72
Peas	28	105.62	1.45	0.26	183.08	3.20
Peas	30	123.67	2.31	0.16	257.38	5.80
Peas	36	160.42	-0.04	4.46	252.05	5.40
Peas	38	180.20	-1.11	12.82	234.42	2.19
Peas	38	97.60	-0.18	9.60	126.05	3.76