The Economic and Environmental Benefits of Partial Leasing of Agricultural Water Rights

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Abstract  Balancing out-of-stream water demands and ecological instream flows is a difficult challenge in watershed-scale management. Many watersheds already experience acute and chronic water shortages during average runoff years and may face more frequent and severe droughts in some locations due to climate and demographic change. Water markets may mitigate the economic consequences of shortages, but their potential is limited by the prevalence of all-or-nothing irrigate-or-fallow crop water use strategies. Irrigation water generally provides diminishing returns for crop productivity, so it may be possible to reduce water application at the margin with only a small loss in crop production, creating water savings that could be leased for other uses. We explore this scenario by combining a crop growth and hydrology (CropSyst) model with an economic model of farm profits and water trading, and apply it to the Walla Walla Basin in Washington State. Our results suggest that partial leasing of water rights through a deficit-irrigation strategy could economically benefit annual crop growers while meaningfully increasing water availability for stream flow augmentation.

1. Introduction

Water management is increasingly complex with divergent competing pressures. While management challenges are exacerbated by drought conditions, in several basins there are significant shortages even under normal or average conditions (Scanlon et al., 2012; Vörösmarty et al., 2000). Moreover, these water management conflicts are expected to worsen under changing climate conditions (Crossman et al., 2013; Rajagopalan et al., 2018). Water markets are a useful management tool to facilitate more efficient allocation of water within agriculture and across other uses such as instream flows, and to enhance strategic water governance goals (Chong & Sunding, 2006; Landry, 1998; Richter et al., 2003). However, there are multiple impediments to well-functioning water markets, which both limit potential benefits of water trading, and affect feasible market structure and water transaction form and function. Transaction costs of water market participation, regulatory administrative costs, legal costs, monitoring costs, institutional transaction costs to adopt transformational policies, uncertainty over water availability, and imperfect measurement of consumptive use all affect water market and water transaction design, participation, and effectiveness (Allan, 1999; Carey et al., 2002; Colby, 1990; Emerick & Lueck, 2015; Garrick, 2015; Libecap, 2008; Loch & Gregg, 2018; Marshall, 2013; Regnaq et al., 2016; Yoder et al., 2008).

In arid and semiarid regions of the Western United States, production of many crops is not possible without some amount of irrigation and associated water rights. Under the Western United States doctrine of prior appropriation, water rights are based on diversions, but water leasing and sales generally transfer only the consumptive use portion of the right to ensure no harm to any third party (Brewer et al., 2007). This necessitates a full accounting of the system water balance including consumptive use and return flow components (Perry & Steduto, 2017; Willardson, 1985); quantifying consumptive use (evapotranspiration) at both fieldscales and watershed-scales is a necessary step for a well-functioning of hydrologically balanced water market. However, evapotranspiration (ET) can be highly variable spatiotemporally, making consumptive use measurement challenging, and mismeasurement problematic for downstream users and stream flow needs (Famiglietti & Wood, 1995; Foster et al., 2020; Long et al., 2014; Tran et al., 2019), creating impediments to water rights transactions.
Irrigation water right leases—a temporary transfer of water rights (Crammond, 1996)—in Washington State (WA) are currently restricted to the full water right, implying that producers choose to either lease the whole right or use it all for irrigating their crops. This may be due to transaction costs related to the ET measurement. It is more difficult for a regulator to monitor and enforce fractional use of a water right and resulting consumptive with a partial lease than to simply observe that a field has been fallowed. A production-based reason is that irrigation water could provide a constant return to yield to a point after which it provides little to no value. Either could induce an all-or-nothing irrigation/lease strategy and dissuade partial water lease arrangements.

If crop yield response supports gains from water trading, an acceptable means of quantifying subseasonal consumptive use could improve the viability for irrigators to lease part of their water right and deficit irrigate (apply less than the full irrigation requirement that would avoid water stress and maximize yields) while maintaining pretrade land in production. The opportunity to lease part of the water right opens the path for water rights transactions beyond current practices, but effective consumptive use monitoring necessitates new technology for more precise and accurate monitoring. While initial investments have been made for improving consumptive use estimates (Allen et al., 2015; FAO, 2020; IMPEL, 2017) further investment will be needed to improve accuracy, frequency and reliability (Foster et al., 2020). An understanding of potential economic benefits of partial leasing is a necessary first-step in assessing the value of investing in subseasonal consumptive use measurements for these purposes. As advances in technologies like satellite-based remote sensing of evapotranspiration, more extensive irrigation metering, soil moisture sensors, and automated irrigation scheduling tools are realized, our perspective is that the feasibility of partial-lease markets will improve. Additionally, whether it is due to these technologies, increasing water scarcity, or crop quality enhancement, deficit irrigation (also known as intensive margin adjustments) is increasingly being recognized as a management decision being used by farmers (Expósito & Berbel, 2016).

Economic models of water reallocation have typically assumed that water and land are used in fixed proportions so that adjustments occur through the extent of irrigated area, or the extensive margin (Arata et al., 2017; Bartolini et al., 2007; Doppler et al., 2002; Gómez-Limón et al., 2016; Graveline et al., 2014; Gutiérrez-Martin & Gómez, 2011; López et al., 2017). There is a relatively new but growing body of the literature focusing on the intensive margin (Chengot et al., 2021; Delorit & Block, 2018; Graveline & Mérel, 2014; Latinopoulos et al., 2014). These studies focus on within-agriculture transfers, and assume a relatively narrow definition of buyers and sellers with some form of cooperative sharing decisions at aggregate spatial scales such as irrigation districts. When there is a large variation in crops and farm characteristics within districts, there can be challenges to cooperative sharing. Although, there are few studies that have integrated crop-water production functions for microeconomic optimization (Graveline & Mérel, 2014; Howitt et al., 2010; Medellín-Azuara et al., 2010) and several others that have integrated agronomic models with micro models (Cortignani & Severini, 2009; Loch et al., 2020; Ortega Álvarez et al., 2004), there is limited existing work focused on the intensive margin and transfers from agriculture to instream purposes. Willis and Whittlesey (1998) compare a range of strategies for augmenting instream flows including deficit irrigation, fallowing, irrigation efficiency improvements and water storage. Peck et al. (2004) use cow-calf operations with irrigated hay production as an example to investigate the potential for short-term leases to transfer water from agriculture to instream flow using a farm budget approach with rough approximations for consumptive use and cooperative decisions.

The objective of this paper is to contribute to the body of work focused on the intensive margin, and to evaluate the extent to which partial leasing can improve economic outcomes for farms and generate meaningful increases in stream flow for ecological needs with minimal reductions in food production. We make a significant advance on previous studies by evaluating alternate deficit-irrigation strategies based on crop growth stages and constructing a yield curve that allows a grower to choose the best strategy. To provide proof-of-concept for potential watershed-scale benefits, we consider two major crops (corn and winter wheat) grown in the Walla Walla River basin in Washington State. Outcomes are evaluated under a range of economic and climate conditions based on a modeling framework that can easily be generalized to other basins. We compare economic outcomes of (a) deficit irrigation and partial leasing, (b) fallowing and leasing the full water right, and (c) using the full water right for crop production. Crop yield response curves to different deficit-irrigation strategies are simulated using a cropping system model—CropSyst (Stöckle et al., 1994, 2003).
These response curves are used to determine how farm revenue varies as a function of crop and water lease prices and the amount of water leased. A partial-leasing water market could take on different forms with varying levels of complexity. Our focus is on leasing markets that operate prior to the beginning of the irrigation season. While a market that allows for trades after the irrigation season starts could have additional benefits, it would require a dynamic and stochastic model of farmer decision making that incorporates the amount of irrigation already used that is beyond the scope of this paper.

Most watersheds in the Western United States are water-constrained and their surface water is fully or near-ly fully appropriated. Further, due to the history of water rights allocation in the West, most rights to stream flow as a beneficial use are junior to most diversion rights, including those held in the agriculture sector. Our focus on leasing agricultural water rights for stream flow augmentation represents a type of transaction that is increasingly important for basin-scale water allocation in the West. We show that partial leasing of agricultural water rights can provide benefits to agricultural water rights holders as well as stream flow augmentation efforts, and can increase the aggregate value of water across competing market and historically nonmarket uses.

### 1.1. Study Area

We focus on the Walla Walla River basin in the Pacific Northwest United States—a watershed that faces substantial competition for water between agriculture and instream flows for ecological needs even in non-drought years, and has been deemed as a critical watershed (Department of Ecology, 2019). In fact, this is a “closed basin” with a Washington Administrative Code rule (WAC 173-532-030, 2007) that prohibits issuance of new water rights from May 1 (day 121) to November 30 (day 306) in two of the Washington State stream segments. Two other segments are closed starting June 1 (day 153) (Table 1). In Oregon State, the watershed is closed to new water rights from May 1 (day 121) to December 31 (day 365) (Oregon Water Resources Department, 2021). The region has existing partnerships across diverse sectors seeking to address water resources concerns through various means including water leasing markets.

The 4,275 km$^2$ (1,650 square mile) watershed encompasses a bistate area located in southeastern Washington/northeastern Oregon (Figure 1). The two major tributaries of this transboundary watershed—Toucet River and Walla Walla River—originate from the Blue Mountains and are fed with numerous small creeks before meeting the Columbia River. Precipitation is highly variable, ranging from an average of 114.3 cm (45 in.) per year in its mountainous headwaters to 25.4 cm (10 in.) per year near its confluence with the
Columbia River. Significant crops include alfalfa seed, alfalfa hay, corn, potato and wheat. In 2018, Walla Walla County produced over 382,377 metric tons (14.05 million bushels) of winter wheat from approximately 631.30 km² (156,000 acres) and 32,740 metric tons (1.29 million bushels) of corn from 23.87 km² (5,900 acres) of irrigated and dryland farming (USDA, 2017). For this study, we focus on the Washington State part of the basin as cross-state water leasing programs have legal complications and are virtually nonexistent.

In our study area, the total irrigated extent is approximately 24,000 hectares with about 10,000 hectares of irrigated wheat and 1,000 hectares of irrigated corn, spatially distributed as in Figure 1. Locations of all the gages with the state-adopted Minimum Instream Flow Rules (MIFR) (WAC 173-532-030, 2007) are displayed in Figure 1 along with an additional USGS gage (WR, State Line) which we use for discharge estimates closer to the outlet of the basin.

Existing MIFR in Washington State for gages listed in Figure 1 is noted in Table 1. A comparison of the MIFR and average discharges is provided for the gage on Detour Rd (Figure 2); the river is unable to meet all existing agricultural, municipal, industrial, and instream flow rights every year. Curtailment of junior water rights occurs every year leading to economic losses and insufficient stream flow to satisfy the MIFR during low summer flow periods. The rules are meant to limit stress on aquatic species such as Steelhead Trout, Spring Chinook Salmon, and Bull Trout, which are all listed as threatened or endangered. MIFR in Washington State are not regulatory mandates per se. They are water rights held by the state much like standard individual water rights, with a priority date that defines seniority relative to traditional diversion rights. The state has no legal basis for curtailing diversions for water rights senior to the MIFR. This means there is a potential for water markets to facilitate water reallocations for stream flow augmentation in most years. For interpreting our results, we use the lowest MIFR in the year (the blue line in Figure 2) as a baseline to assess augmentation potential of lease markets.

2. Materials and Methods

We first describe and provide context for the irrigation strategies that we compare in our analysis. We then describe the CropSyst model and our utilization of it, followed by an analytical economic model describing the water allocation decision between irrigation and leasing, and a description of the data used for simulation.
2.1. Fallowing and Deficit-Irrigation Strategies

When a field is fallowed no crop is grown and the full water right is leased. Forgone crop yields are simulated by the CropSyst model.

Different irrigation strategies provide crop-specific yield and economic benefits (Costa et al., 2007). We examine four deficit-irrigation scenarios (Figure 3). All scenarios start with CropSyst model simulations of an irrigation schedule assuming no deficit corresponding to potential maximum yields. Using this baseline full irrigation schedule (henceforth FIS), different strategies apply deficits during different stages of the growth season. Constant percentages of deficit from 0% (FIS) to 100% (no irrigation) are applied at increments of 10% to the FIS—at time frames specific to each strategy—to obtain the yield response curve to varying amounts of deficit. The sum of the differences between the FIS and deficit-irrigation applications provides the tradable water volumes for each strategy. A deficit percentage of 40% would mean that 60% of the

![Figure 2](image-url)

**Figure 2.** Average daily stream flows (2013–2018) at Detour Road, Walla Walla, WA (Department of Ecology Gage No. 32A100) with state-adopted minimum instream flow values. Blue dotted lines inside the shaded area (time period when the basin is closed to new water rights because of insufficient stream flow) is the assumed minimum instream flow requirement—the lowest state-adopted instream flows.

![Figure 3](image-url)

**Figure 3.** Diagram of the deficit-irrigation strategies considered. For each strategy, the solid bidirectional arrow corresponds to durations with full irrigation applications and dotted arrows correspond to durations with deficit-irrigation applications. Vertical color band (corn: blue, wheat: green) at the bottom shows the average monthly calendar for two crops.
irrigation application corresponding to FIS will be applied in the appropriate deficit timeframe (Figure 3). A total of 40 deficit simulations were performed across all deficit strategies with six realizations of weather for corn and five for winter wheat per simulation for a total of 440 realizations.

2.1.1. Continuous Deficit All Season (CDAS)
Continuous deficit percentages are applied to FIS throughout the entire growing season.

2.1.2. Continuous Deficit Except During Flowering (CDEF)
Numerous studies have shown that irrigation during flowering is critical for maintaining yields (Campos et al., 2004; Kumar Jha et al., 2019; Li et al., 2005; Nissanka et al., 1997). This scenario assumes that farmers will provide the FIS during flowering but deficit irrigate at all other times to avoid stress during flowering. For example, providing 60% of the irrigation demand (40% deficit) means reducing irrigation amounts by 40% outside the flowering period but maintaining full irrigation during flowering.

2.1.3. Continuous Deficit After Flowering (CDAF)
Based on the same motivation described in the prior strategy, this scenario provides for full irrigation from sowing through flowering followed by deficits after the flowering period ends (early July for corn and late June for wheat). Because deficits are applied over a shorter duration than CSAS or CDEF, the total unapplied irrigation water that is available for trading will be lower in this scenario than the CSAS or CDEF scenarios.

2.1.4. Continuous Deficit After June 1 (CDAJ1)
As indicated previously in Figure 2, the basin is closed to any further water diversions because instream flow shortages occur every summer creating a demand for stream flow augmentation beginning in June. Therefore, we simulate a strategy of deficit applications after June 1, given it may not be possible to bank or store earlier savings to make them available after June 1.

2.2. The CropSyst Model
The CropSyst model is a process-based cropping systems model that simulates many aspects of these systems including crop development, growth and yield soil water and nitrogen budgets and carbon cycles (Stöckle et al., 1994, 2003), using hourly to daily integration time steps. The model has been widely used to study the effect of climate, atmospheric carbon concentration, soil and management on crop productivity as well as the environmental impacts of cropping systems (e.g., Anwar et al., 2007; Bocchiola et al., 2013; Karimi et al., 2017; Malek et al., 2018; Sommer et al., 2012; Stöckle et al., 2018). A review of different types of applications of the model and future developments were presented in Stöckle et al. (2014). Directly relevant to this study, a recent study on drip-irrigated and sprinkler-irrigated wheat in Egypt compared CropSyst with experimental data including a number of deficit-irrigation strategies, with the authors indicating excellent agreement between model outputs and observations of yield responses to water applied in Noreldin et al. (2015). CropSyst first estimates potential biomass production based on crop potential transpiration and crop-intercepted solar radiation (SR). The potential biomass production for the day \( B_{PF} \) is taken as the minimum of transpiration-based \( B_{PT} \) and solar radiation-based \( B_{SR} \) biomass accumulations given by Equations 1 and 2, respectively:

\[
B_{PF} = \frac{K_{BT}T_p}{VPD}
\]

\[
B_{SR} = eISR
\]

where \( B_{PF} \) is the crop potential transpiration-dependent biomass production (kg/m\(^2\)/day), \( T_p \) is crop potential transpiration (kg/m\(^2\)/day), VPD is the daytime mean atmospheric vapor pressure deficit (kPa), \( K_{BT} \) is a biomass-transpiration coefficient (kPa), \( B_{SR} \) is the intercepted SR-dependent biomass production (kg/m\(^2\)/day), \( e \) is the radiation-use efficiency (kgM/J), and ISR is the daily amount of crop-intercepted solar radiation (MJ/m\(^2\)/day).
Estimated potential biomass production is then adjusted for water and nitrogen limitations, if any, to determine the actual biomass production. In the case of water, potential transpiration is adjusted to the actual value as limited by root soil water uptake, which depends on soil water content, rooting depth, and the profile distribution of root fractions active in water uptake (Jara & Stöckle, 1999; Stöckle & Jara, 1998). The yield \( Y \) is calculated by multiplying total biomass accumulated at physiological maturity \( B_{pm} \) with harvest index \( HI \):

\[
Y = B_{pm}HI
\]  

(3)

where \( Y \) and \( B_{pm} \) are in \( \text{kg/m}^2 \) and \( HI \) is the harvest index, the fraction of harvestable yield to above ground biomass that is responsive to water and heat stress. For more information on model details and equations, readers are referred to Stöckle et al. (1994), Stöckle and Jara (1998), and Stöckle et al. (2003).

In our work, the CropSyst model is used to simulate changes in crop yields for irrigated grain corn and winter wheat fields under four deficit-irrigation scenarios (Figure 3) with no nitrogen limitations. The study period is (2013–2018). For each deficit-irrigation strategy, the model was first run to determine full irrigation net demands based on seasonal variations in weather, soil water content, and root depth and distribution. The demand amount is equivalent to consumptive use requirements without adjustments for irrigation efficiencies and seepage/runoff losses. Subsequent runs were then made supplying a fixed fraction of the full irrigation demand for each irrigation event (e.g., supplying 80% of demand or 20% deficit irrigation) to create the different scenarios depicted in Figure 3.

### 2.3. Economic Model of Irrigator Decision

The farmer's problem represented in the economic model is to choose how much of their water right to lease out versus retain to irrigate their own crop in the presence of a water leasing market. From the farmer's perspective, the existence of a leasing market increases the opportunity cost of using water to irrigate their own crops, because to do so, they forego revenue that they could receive for leasing all or part of their water rights. We examine three basic lease outcomes: an all-or-nothing lease in which either an entire water right is retained for irrigation or sold for lease revenue; and a partial lease, through which part of a water right is leased away, and limited irrigation is pursued with remaining unleased water under the right.

Most farms engage in multiinput, multioutput production and are primarily focused on profitability. They choose a combination of inputs and outputs that they expect will maximize their objective(s) subject to multiple resource constraints and uncertainty over future conditions like weather and market prices.

Models represent these components in varying detail depending on data availability, the research question, modeling capabilities, and understanding of real-world behavior. We begin with a relatively general model of a multiinput, multioutput profit maximization problem, and impose a number of simplifying assumptions to focus on the essential elements of our primary research question. The simplified model amounts to a constrained single-input single-output profit maximization problem.

Consider a farm that allocates multiple inputs to produce multiple crops to maximize restricted, or short-run, profit subject to cultivated area \( A \), a water right that allows a certain amount of consumptive water use \( W \) from a diversion right that can be allocated across a variety of crops or leased to others, subject to input nonnegativity and yield feasibility constraints:

\[
\max_{\{x, a, w\} \geq 0} \Pi = \sum_{i=1}^{I} \pi_i = \sum_{i=1}^{I} \left( p_i a_i y_i - bx_i - rw_i - d_i \right) 
\]  

(4)

subject to

\[
\begin{align*}
\sum_{i=1}^{I} a_i &\leq A \\
\sum_{i=1}^{I} w_i &\leq W \\
y_i &\leq g_i(x, w_i, v, s)
\end{align*}
\]

Total production of crop \( i \) is given by \( q_i = a_i y_i \), where \( a_i \) is area cultivated and \( y_i \) is yield for crop \( i \). For multi-input production, yield is a crop-specific function \( g_i(\cdot) \) of irrigation water consumptively used by the crop.
(w), a vector of other variable inputs (x), and vectors of stochastic and fixed factors that affect crop production such as weather (v) and soil (s), respectively. Prices in the model are the crop price (p), the price that would be received by a farmer per unit of leased water (r), which is assumed exogenous from the perspective of agricultural rights holders, and a vector of prices for other variable inputs (b). Other production costs for crop are included as d.

Variations on this general set-up can be found in many different regional-scale models of irrigated agriculture. Many studies assume Leontief production technology with water and land used in fixed proportions, which precludes intensive margin adjustments, and implies that reduced water use leads to either fallowing or rainfed production (Arata et al., 2017; Bartolini et al., 2007; Doppler et al., 2002; Gómez-Limón et al., 2016; Graveline et al., 2014; Gutiérrez-Martín & Gómez, 2011; López et al., 2017). Precluding intensive-marginal adjustments to water use in modeling and/or estimation may bias estimates of the economic impacts of drought upward significantly (Frisvold & Konyar, 2012). In contrast, we build on the small but growing literature focusing on intensive margin changes in irrigation water use (Chengot et al., 2021; Delorit & Block, 2018; Expósito & Berbel, 2016; Graveline & Mèrel, 2014; Latinopoulos et al., 2014), which is informed by many studies on irrigation technology and water use efficiency (Perry & Steduto, 2017; Willardson, 1985).

Many of the studies noted above are based on mathematical programming model simulations that use calibration procedures for parameterization so that factor allocation and production predictions are consistent with observed values (e.g., Howitt, 1995; Heckelei & Wolff, 2003). In this vein, we utilize the CropSyst simulation model as described above, which provides a biophysical crop water-yield relationship with diminishing returns to water application around maximum yield—a near-necessary condition for modeling economical deficit irrigation.

To focus our modeling efforts, we break apart the multioutput problem into separate single-crop models for corn and wheat because it is more informative to show how the potential of a partial-leasing market depends on the curvature of the crop water-yield relationship than making a region-level water reallocation prediction. To attune the model to our region of study, we set crop-specific maximum acreage (A) and irrigation water consumptive use (W) to the observed current allocations for corn and wheat in the Walla Walla Basin.

We also simplify our model by treating irrigation water as the only choice variable based on the following assumptions: levels of other variable inputs are fixed; weather is consistent with a historical average that is known with certainty by the farmer when the leasing decision is made (F); and local fixed growing conditions are homogeneous and represent an average for the region of study (S). Following from these assumptions, let f(w) = g(w,x,F,S) to simplify notation.

Treating nonwater inputs as fixed abstracts from potential optimal adjustments to inputs such as fertilizer and labor in conjunction to partial water leasing and changes in irrigation intensity. Fertilizer and irrigation are typically complements, so fertilizer application rates per hectare would decrease if water leasing led to intensive margin adjustments, and simulated profit from leasing would be higher if this relationship were accounted for. However, empirical studies have shown that farmers often fail to reduce fertilizer use when it is profitable to do so (e.g., Babcock, 1992). Similarly, labor and water are likely to be substitutes when deficit irrigating because a farmer may spend more time checking soil moisture levels and crops for signs of water stress in the absence of technology that automates these tasks. Factoring in higher labor costs with partial leasing would reduce our profitability estimates. Adding interactions across inputs will add complexity, without significant contributions to our analysis.

Locally fixed but regionally heterogeneous growing conditions (S) are treated as regionally homogeneous (S̄) in the process of fitting regional yield curve to pseudodata from crop model simulations such that they are consistent with average, or typical, conditions (see Section 3.1). While this does result in some loss of regional detail, it greatly eases discussion of results because the optimal per hectare share of water leased is constant across all land growing a particular crop. In other words, the supply curve for water to the leasing market is horizontal as opposed to the typical upward sloping supply curve. As a result, we can specify our model on a per-hectare basis and drop the region-level crop-specific cultivated area constraint (A) when deriving the optimal decision rule. It is considered when reporting regional level results.
Similarly, the fitted yield curves reflect the mean of historical conditions ($\overline{W}$). From the representative decision maker’s perspective, we assume farmers treat the fitted curve as “the” true yield curve for a crop in a given region, known with certainty at the beginning of the growing season. This is conceptually similar to maximizing expected profit based on expected values of weather outcomes and assuming the farmer is risk neutral. As such, our results might be taken as an upper bound on ex postfarm profit in the sense that any other irrigation decision would lead to lower profit under the same realized weather conditions. We derive optimal water leasing quantities based on expected weather corresponding to a climate average.

In regard to $f(w)$, diminishing returns for irrigation water holds within CropSyst, so $f(w)$ is nonmonotonic and decreasing beyond the maximum yield point. Fitting a cubic polynomial—

$$f(w) = \beta_0 + \beta_1w + \beta_2w^2 + \beta_3w^3$$

where $\beta_j$’s are parameters—to the pseudodata from CropSyst model runs results in yield decreasing beyond the level of water ($W$) that maximizes yield. See Section 3.1 for a detailed discussion of how different deficit-irrigation strategies are combined to create a single functional relationship between irrigation water and yield. It is common in our area of study for surface water rights to permit application rates that correspond to consumptive use greater than $w_{\text{max}}$. In other words, farmers have access to enough water to over-irrigate their crop. The optimal irrigation level ($w^*$) is considered over the domain where $w^* > 0$, $f'(w) \geq 0$, and $f''(w) < 0$ where single and double primes represent first and second derivatives.

Input and output prices may be viewed as stochastic at the time planting and water leasing decisions are made, but there are plausible reasons for treating them as nonrandom. Crop spot prices received at harvest time are not known at planting or even during irrigation, but farmers have many tools for limiting or eliminating price risk, including futures and options markets, grower contracts that set price, and USDA insurance programs. For the water price, we conceive of the buyer as an institutional buyer of water to augment instream flows who publicly post the price they are willing to pay for the season. This is consistent with some instream flow augmentation activities in Washington State in the past ("Partnership Purchases," Partnership Purchases Water Rights From Willing Washington Landowners as a way to Increase Streamflows in the Basin, n.d.).

Taken together, these specifications simplify the crop $i$ profit maximization problem to $\max p_i f_i(w) - rw$. Differentiating with respect to $w$ and setting equal to zero gives $p_i (\partial f_i / \partial w) = r$ or $\partial f_i / \partial w = r / p_i$. Figure 4 illustrates this optimality condition for irrigation in both total benefits and opportunity costs (top panel), and marginal benefits and opportunity costs.

For a range of water lease prices along the x axis, Figure 5 compares the economic outcome of a partial-leasing strategy (solid black line) to those from the all-or-nothing alternative—where the full water right would either be used for producing crops or leased in full. The green line corresponds to revenue from using the full water right to produce a crop (assuming one fixed crop price) and is a straight line with zero slope as it is independent of water lease prices. The solid part of the green line (zone 1) corresponds to very low water leasing prices ($< r_f$) where the optimal strategy would be to grow crops. The blue line corresponds to revenue from fallowing and leasing the water right in full, and increases linearly with water lease prices. The solid part of the blue line (zone 3) corresponds to high water lease prices ($> r_f$) where fallowing would be the optimal strategy. The nonlinear solid black line (zone 2) for the middle range of water lease prices ($r_f - r_c$) corresponds to revenue from partial leasing where that is the optimal strategy. This is specific to one crop price assumption; a change in crop price will shift the green line which will shift the black line as
Zone 2 can be considered as encompassing two regions. In Zone 2a, the next best alternative to partial leasing is using the full water right to grow the crop (the green line is higher than the blue line). In this region, the additional revenue (difference in revenues between partial leasing and the next best alternative) increases with water lease prices. In Zone 2b, the next best alternative to partial leasing is fallowing (blue line is higher than the green line), and the additional revenue decreases with water lease prices. That is, the additional revenue curve (lower left corner of Figure 5) increases nonlinearly from $r_1$ until a water lease price of $r_2$ and then decreases nonlinearly until it becomes zero at $r_3$—the transition point to fallowing as the optimal strategy.

2.4. Input Data Sets

2.4.1. Weather Data

Hourly and daily weather data were acquired from the U.S. Bureau of Reclamation (USBR) Agrimet Network weather station at Legrow (LEGW), Washington. Variables include the maximum and minimum air temperature ($T_{\text{max}}$ and $T_{\text{min}}$), maximum and minimum relative humidity, wind speed, solar radiation, and precipitation for our study period of 2013–2018.

2.4.2. Soil Data

The soil data, in the form of percentage of sand, silt, and clay, required to estimate soil properties in CropSyst was extracted from the USDA Natural Resource Conservation Service (NRCS) web soil survey at three depths (0.1, 0.3, and 1.0 m) from the surface (NRCS, 2006). The soil data was then used to estimate soil properties using the built-in CropSyst soil texture selection tool.

2.4.3. Crop Layer Data

The crop layer data required for this study were extracted from the Washington State Department of Agriculture (WSDA) crop layer data (WSDA, 2018). WSDA surveys about one third of Washington State each year and our region of interest was surveyed in 2018 which was used to identify the appropriate corn and wheat areas.

2.4.4. Stream Discharge Data

The stream flow discharge required for this study was acquired from the Washington State Department of Ecology through a personal correspondence.

2.4.5. CropSyst Parameters

The crop parameters used for the corn and wheat crops modeled in this study are provided in Table A1.
2.4.6. Crop Prices Water Lease Prices and Production Costs Data

Daily prices per bushel of wheat and corn were extracted from the open source Macrotrends website (macrotrends, 2019). Over the last decade corn prices have ranged from $0.12 to 0.33/kg (average: $0.18/kg) whereas wheat prices ranged from $0.14 to 0.35/kg (average: $0.21/kg). Based on this, we used a price range of ($0.1 to 0.35/kg) for both crops. These are market prices and may not reflect payments received by farmers, which may differ due to The Agriculture Risk Coverage (ARC) and Price Loss Coverage (PLC) program subsidies.

Water lease prices are not readily available as other data sources. We simulate a range of water prices from $0 to $9/ha mm at intervals of $0.01/ha mm. This range encompasses water lease prices from Arizona, Texas and California compiled in Schwabe et al. (2020) and lease prices of $800/acre noted in Washington State in the 2015 drought year (correspondence with the Roza Irrigation District).

There are numerous factors impacting production costs including farm size and assumptions concerning equipment and farm management practices (Delbridge et al., 2011, July 24–26, 2011; Key, 2018). For this study, we used two USDA studies that reflect average costs across the country for corn and in the Pacific Northwest for wheat (Meade et al., 2016, June 2016; Vocke & Ali, 2013, August 2013). Costs were converted to consistent 2015 dollars using appropriate inflation factors. The fixed costs are common across all strategies compared and what matters in our case are the planting costs referenced in Section 2.2.3 and Figure 5—$772.6/ha and $442.13/ha for corn and wheat, respectively (Meade et al., 2016, June 2016; Vocke & Ali, 2013, August 2013).

3. Results and Discussion

This section starts with the estimated crop production function for each deficit-irrigation strategy and provides the simulated yields under different deficit-irrigation strategies and levels of deficit. This is followed by details of the revenue maximizing water application amount, and the corresponding water leasing amounts available for instream flow augmentation and associated reductions in crop production. The additional revenue potential of a partial-leasing strategy (when it is the profit maximization strategy) is described next. Finally, we provide a basin-scale estimate of the potential for instream flow augmentation at various assumed levels of adoption of partial-leasing strategies.

3.1. Crop Production Function

Crop production functions (yield as a function of water use) for the four chosen deficit-irrigation strategies are fit as third-degree (cubic) polynomial equations (Figure 6). This polynomial fit was generated in R version 4.0.3 using the “stat_smooth” function in the “ggplot2” package. We used the linear model “lm” with the default significance level of 0.05 for computing confidence intervals (via an internal call to the “predictdf” function). The corresponding R-square values are displayed as well. The R-square values are above 0.85 in all cases except in the case of wheat for the two deficit strategies that start later in the season (deficit after flowering, and deficit after June 1) for wheat. Winter wheat has a higher interannual variability in full (no deficit) irrigation requirements as precipitation is a more important contributor of water use in wheat than for corn (precipitation accounts for 16–37% of wheat water use, depending on the year as opposed to 5–12% for corn). This results in a high variability in the yield response for specific deficit water amounts as well, especially when they are concentrated at the end of the season. This is also apparent as five potentially distinct curves corresponding to each year (see the plot corresponding to deficit starting after flowering) while the R-square values correspond to one fitted curve across all data points to get an approximate average response across multiple years of data.

The production function \( f \) is yield in kilograms per hectare (kg/ha) per year. Irrigation amounts are in millimeters per year. While Figure 6 displayed the production functions individually for each deficit strategy, Figure 7 shows them in combination to allow comparisons across strategies. In general, strategies that avoid water deficits during the critical flowering period—either by restricting deficit strategies to after completion of flowering or by restricting deficit to before and after flowering—have higher yields for a given amount of irrigation. This is consistent with the literature (Geerts & Raes, 2009; Istanbulluoglu et al., 2010; Payero
et al., 2006). However, restricting deficit irrigation to after flowering reduces the amount of water that could potentially be leased as significant portions of the water rights have already been applied.

Figure 7 shows that the CDAF is the best deficit-irrigation strategy if the amount to be used toward irrigating the crop is greater than \( \sim 200 \text{ mm/yr} \) (\( \sim 42\% \)) and \( \sim 300 \text{ mm/yr} \) (\( \sim 62\% \)) for corn and wheat, respectively. Similarly, for irrigating amounts less than these values, the best strategy would be the CDEF. For a better approximation we developed continuous functions using these two optimal conditions to produce an “envelope” yield response—an average year approximation of the best yield response across all strategies for a given water application amount. Each envelope production function (black curves) is fit over points corresponding to the best deficit strategy under each irrigation application amount for each year. This is CDEF for the lower part and CDAF for the higher part of the curve. An alternative approach would have been to use the envelope of the curves of the different strategies. However, this would result in a single function that is not differentiable over the entire range, which significantly complicates the computation and display of results for little gain. The envelope can be considered as the proxy fit for the best strategy (which will be different for different irrigation application amounts). The production function for this envelope strategy (Equations 6 and 7) has \( R \)-square values of 0.93 and 0.86 for corn and wheat, respectively. Table 2 provides the significance of each coefficient for Equations 6 and 7.

\[
f(w) = 1870 - 13.8 \cdot w + 0.193 \cdot w^2 - 0.000246 \cdot w^3
\]  

Figure 6. Yield curve (blue: wheat, black: corn) under four chosen deficit-irrigation strategies with the shaded region representing the 95% confidence interval. Scatter points in each subplot represent the variation in yield (productivity) with the variation of irrigation application amounts and curve is the third-degree polynomial fitted for each deficit-irrigation strategy.
\[ f(w) = 1680 - 14.4 \cdot w + 0.116 \cdot w^2 - 0.000139 \cdot w^3 \]  

(7)

From hereon, we focus on results using the envelope production function. That is, for further analysis we assume that the optimal irrigation strategy is chosen.

### 3.2. Revenue Maximizing Water Application Levels

The revenue maximizing water application levels for a range crop and water lease prices are shown in Figure 8. These correspond to the revenue maximizing condition derived in Section 2.3 \[ f^* = \frac{r}{p_i} \]. The optimal amount of water growers should retain for irrigation varies from 397 to 484 mm for corn, and 408–484 mm for wheat. For example, at a corn price of $0.20/kg and water lease price of $2/mm ha, irrigators will want to retain ~451 mm water for irrigating the crop while leasing the remainder. For the same crop and water leasing prices, corn growers will lease out less water than wheat growers (Figure 8) because the productivity of corn per unit area is higher than that of wheat (Figure 7). The yellow area in the plot corresponds to low water lease prices where the revenue maximizing condition is to apply the full water duty (~484 mm) to grow the crop. The gray shaded area corresponds to price ranges where the revenue maximizing decision is to fallow and lease all the water. These results indicate that for plausible historical ranges of crop and water leasing prices, there are several instances (blue and green areas) where partial leasing is more profitable than the all-or-nothing alternatives (fallow and lease all water or use the full water duty for crop production).

### 3.3. Water Leasing Potential for the Irrigation Strategy

When deficit irrigation is the profit maximizing strategy, Figure 9 shows the magnitude and percentage (over the full irrigation requirement) of the water leasing potential. For example, at a water leasing price of $3/ha mm and crop price of $0.35/kg, the optimal amount of water available for leasing with corn and wheat will be 28 mm (5.8%) and 57.5 mm (11.8%), respectively. For lower crop prices there is a smaller range of water lease prices where deficit-irrigation results as the optimal strategy.
For higher crop prices (yellow part of Figure 9), there is a wider range of water lease prices where deficit-irrigation strategies are optimal. Less than 20% of irrigation water use is tradable under the optimal deficit irrigation (see right Y axis of Figure 9), so significant production acreage will have to adopt deficit-irrigation strategies for farm-level leasing to translate into meaningful quantities of stream flow augmentation at the watershed-scale.

**Figure 8.** Optimal amount of water retained for irrigation under deficit-irrigation strategies with varying prices of crop (color) and leasing prices of water (Y axis).

**Figure 9.** Optimal amount of water available for leasing for varying crop prices (in color) and water lease prices (X axis). The first Y axis is the optimal amount of water available for leasing and the second Y axis is this amount expressed as a percentage of the full irrigation demand.
3.4. Reduction in Crop Production

While a revenue maximizing deficit-irrigation strategy increases revenue for farmers and provides water for leasing, it does come at the cost of reduced crop production. This could be an important consideration in the aggregate for society if partial leasing were to be widely adopted. The loss is calculated by deducting the yield corresponding to the revenue maximizing irrigation amount from maximum yield under full irrigation (assuming that the farmers will lease out the remaining water). Figure 10 shows the magnitude and percent production lost under varying crop and water lease prices. For example, at a water lease price of $3/ha·mm and crop price of $0.35/kg, the loss in corn and wheat production are $123 kg/ha (0.98%) and $260 kg/ha (4.25%), respectively. These correspond to leasing 5.8% and 11.8% of the water right (Figure 8).

3.5. Additional Revenue From Deficit Irrigation Over Full Irrigation or Fallowing

One of our primary objectives is to evaluate the additional revenue potential from facilitating a partial-leasing market as opposed to the existing all-or-nothing option. The additional revenue from adopting a deficit-irrigation strategy (when it is the revenue maximizing strategy) is obtained by comparing the optimal deficit-irrigation strategy’s revenue with the revenue from the next best alternative (full irrigation or fallow). For a given crop price, additional revenue as a function of water lease price increases to a maximum and then decreases (see Figure 5 in the methods section for explanation). The relationship is upward sloping where retaining all water for crop production is the best alternative. It slopes downward when the best alternative is leasing all water (fallow). Figure 11a shows the additional revenue in the case of corn for two example prices—the low and high ends of the full crop price range. Figure 11b shows results for the full range of prices, including the two example prices used in Figure 11a for both corn and wheat.

Consider a corn price of $0.35/kg (yellow line in Figures 11a and 11b). For low water lease prices, the additional revenue from deficit irrigation increases until it reaches a water leasing price of $7.43/ha·mm with an additional revenue of $270.57/ha. As the water lease price increases, the additional revenue from a deficit strategy decreases to zero. At this point, the revenue maximizing option is to fallow and lease all water. There is no further additional revenue from deficit irrigation as it is no longer revenue maximizing. This transition point is at a much lower water lease price for lower crop prices—water lease price of $0.97/ha·mm for a corn price of $0.10/kg versus a water lease price of $7.43/ha·mm for a corn price of $0.35/kg (Figure 11a).
3.6. Basin-Wide Potential for Instream Flow Augmentation

We have shown that partial-leasing markets have the potential to increase farmer revenue while only reducing crop production slightly for over a wide range of conditions that could occur. In this section, we explore whether the water available for instream flow augmentation is meaningful from a hydrological perspective. This analysis is very specific to area of study, but the approach described is general.

Total irrigated hectares for corn and wheat in the basin are around 1,000 and 10,000 hectares, respectively (WSDA, 2018). Given that the revenue maximizing water application amounts are relatively high—the water leasing potential is not more than 20% of full irrigation demands (Figure 9)—and the yield maximizing deficit strategy for these application levels is to apply the deficit after flowering (Figure 7), we use the time frame between the flowering and maturity to calculate stream flow augmentation potential (Figure 12). On average, this allows stream flow augmentation for around 55 days for corn (July and August months) and 25 days (June and July months) for wheat. We calculated the average augmented discharge based on these time periods for corn and wheat, respectively, for different levels of basin-scale adoption of deficit-irrigation.

![Graphical representation of additional revenue and leasing price](image-url)
strategies ranging from 0% adoption (no one adopts; historical baseline average discharges) to 100% adoption (adoption by 100% of crop acreage) in increments of 25% (Figure 12). Figure 12 is based on the maximum leasing potential and should be considered an upper bound of instream flow augmentation potential.

If 50% of the irrigated wheat acreage adopts a profit maximizing deficit-irrigation strategy, average stream flow increases $\sim 1.77 \, \text{m}^3/\text{s}$ between June 20 and July 14 (difference between solid black and solid blue lines in Figure 12). Corn acreage is significantly lower, and therefore if 50% acres adopt a deficit strategy, the basin stream flow augmentation potential drops to about 0.09 \, \text{m}^3/\text{s}. These values can also be considered in the context of the state-adopted minimum instream flow requirements—7.075 \, \text{m}^3/\text{s} between June and November for the Walla Walla River mainstem (Figure 2)—to get a relative sense of augmentation potential. If 100% of the wheat acreage in the region adopts partial leasing, the augmented flows will allow historical discharges to reach the minimum requirements in the later part of June. Even if 100% of wheat and corn acres adopt deficit irrigation, augmentation will not be sufficient to increase stream flows to the minimum instream requirements in July. Nevertheless, the July average discharge has the potential to increase by 330% with 100% adoption in the wheat extent. These results suggest that even large-scale adoption of deficit irrigation by corn and wheat growers alone will fall short of reaching a goal of meeting the MIFR, especially later in the season. However, we hasten to add that the marginal value of any stream flow augmentation in low-flow periods may be high, regardless of reaching the MIFR benchmark. Moreover, partial leasing should be viewed as one option in the toolbox for augmenting instream flow and achieving MIFR benchmark goals will require a broad array of strategies such as improved irrigation efficiency, managed aquifer recharge, water conservation, enhancement of reconnection of spring-fed wetlands, voluntary water transactions for instream flow restoration, and managing forested areas to maximize snow/water retention (Lane & Rosenberg, 2020).

These estimated stream flow augmentation potentials are near the outlet of the basin, and therefore only stream reaches close to the outlet will benefit from this level of augmentation. Upstream locations and tributaries will have progressively lower augmentation potential depending on the spatial distribution of irrigated acres (Figure 1). However, tributaries also have lower minimum flow requirements than the Walla Walla River mainstem (Table 1) and therefore significant relative augmentation potential still exists for

Figure 12. Average stream flow with and without adoption of a deficit irrigation and leasing strategy for corn and wheat. The X axis represent the Julian day of the year and Y axis gives the corresponding average river discharge. Multiple basin-level adoption rates of deficit strategies are assumed (ranging from 0% to 100% of crop acreage adopting the strategy in increments of 25%). The solid black 0% adoption line corresponds to baseline current average discharges for comparison. The dotted black line corresponds to the minimum instream flow requirement for comparison.
tributaries. There is a temporal dimension to the augmentation potential as well, with highest potential augmentation in the later part of June (Figure 12). While May is a critical low-flow month in several parts of the basin (flows are so low that the basin is closed to new water rights as noted in Section 1.1), optimal deficit-irrigation strategies do not result in water savings in May and therefore augmentation potential is likely negligible in May. Winter wheat is harvested by mid-July and therefore there is little augmentation potential for critical low-flow months post-mid-July. With relatively smaller irrigated acres, augmentation potential from corn is limited in this basin. Moreover, most irrigated corn acreage is concentrated near the outlet of the basin (Figure 2) and augmentation will only impact a small stream segment downstream of this acreage.

4. Conclusions

Our results provide evidence and proof-of-concept that partial-leasing markets (which are not currently prevalent) can create win-win options for annual crop growers and stream flow augmentation efforts that exceed the predominant all-or-nothing approach. Our research demonstrates that such a market can have positive impacts for farm revenue and instream flows with minimal impacts to regional food production. As illustrated in Figures 6 and 7, a variety of deficit-irrigation strategies can be explored to facilitate partial lease markets. While the purpose of this work was not to identify the best strategy for every situation, consistent with the literature (Geerts & Raes, 2009; Istanbulluoglu et al., 2010; Payero et al., 2006), our results do indicate that strategies that avoid stress during critical flowering stages will likely be the strategies with the smallest production impacts. This restricts the timing for flow augmentation between flowering and harvest, unless mechanisms to bank and store water savings (such as ponds or reservoirs) and make them available for instream augmentation later in the year exist. The amount of deficit that leads to win-win situations is a smaller fraction (~16% of the full irrigation demand for wheat). Therefore, for farm-level leasing to translate into meaningful stream flow benefits for the region, a significant amount of irrigated production area would need to adopt this practice. For example, our results indicate that for a 100% increase in June-July stream flow, ~31% of irrigated wheat acreage needs to adopt optimal deficit-irrigation strategies. Therefore, for practical success, policies that support incentive structures for adoption will be critical. We should note that overall basin-level augmentation potential will be higher than our estimates as we have only considered two crops—making up roughly half of the total irrigated acres in the basin—in this analysis.

Although our study is focused on the Walla Walla region and two specific crops, the implications are generalizable to other regions with the understanding that crop response to deficit irrigation will vary (Geerts & Raes, 2009). While the magnitude and timing of benefits of partial-leasing strategies may vary significantly from one basin to another depending on several factors including the crop mix, and spatial distribution of irrigated acreage, they are useful for contexts such as those in the Walla Walla River basin where water is scarce and agricultural users are upstream of where instream benefits are needed. Annual grain crops are possibly the best candidates for partial leasing. Perennial crops can be adversely affected by continued water stress for multiple years and therefore not ideal candidates in the context of deficit irrigation (Tombesi et al., 2018). Future research is needed to clarify these crop-specific nuances on the response to deficit irrigation.

The win-win situation for partial lease markets provides additional justification for investments in cost-effective and reliable consumptive use measurements and monitoring—critical for the consumptive use-based water markets of western United States to succeed. In order for a partial-leasing market to be facilitated we would need investments in acceptable within-season measurements of consumptive use for monitoring and enforcement. Extensive metering is lacking (Marston et al., 2018), and while remote-sensing approaches to consumptive use measurements—either drone-based (Aboutalebi et al., 2019) or satellite-based (Zhang et al., 2016) have shown potential, significant gaps remain in their utility (Foster et al., 2020). Moreover, ET observations in irrigated agricultural regions are limited (Zitouna-Chebbi et al., 2018). Investments to address these gaps are critical. In addition, practical implementation of deficit-irrigation strategies would benefit from development of appropriate irrigation scheduling tools, and technological and institutional innovations that reduce transaction costs in water markets generally (Garrick et al., 2013; Wang, 2012). Basin-specific economic and hydrological/ecological benefits of partial-leasing strategies demonstrated in this work can justify these necessary future investments.
Finally, it is important to acknowledge several necessary simplifications in the decision-making process that were considered beyond the scope of the current project. All yields and tradable water amounts were based on average year values meaning that decisions made later in the year did not reflect the actual growing conditions being experienced by the crop. The trades did not account for any changes in irrigation return flows which may lead to unintended third-party damages. This impact assessment, as pointed out by Qureshi et al. (2010) and de Graaf et al. (2014), depends on understanding specific irrigation efficiencies, soil types, identification of specific field, and other factors that will ultimately need to be considered in order to facilitate trading. Future work could address these dimensions, as well as formulating a more complex economic model that accounts for price discovery to allow the buyer to represent an agricultural interest. Allowing market participation decisions to be made any time during the growing season could also provide additional insights.

Appendix A

Table A1 presents the crop parameters used for CropSyst simulation for both winter wheat and grain corn.

| Table A1 | CropSyst Parameters Used in the Base Model |
|----------|-------------------------------------------|
| Crop name | Winter wheat | Grain corn |
| Harvested part | Grain | Grain |
| Photosynthetic pathway | C3 | C4 |
| Life cycle | Annual | Annual |
| Growth parameters | | |
| Radiation-use efficiency at low VPD (g/MJ) | 1.5 | 2.2 |
| Water use efficiency at 1 kPa (g/kg) | 4.3 | 7.5 |
| Leaf water potential that begins reducing canopy extension (J/kg) | −1,200 | −1,200 |
| Leaf water potential that stops canopy expansion (J/kg) | −1,400 | −1,400 |
| Optimum daily mean temperature for growth (°C) | 20 | 20 |
| Canopy cover parameters | | |
| Initial canopy ground cover (0–1, unitless) | 0.001 | 0.001 |
| Maximum canopy cover (0–1, unitless) | 0.95 | 0.95 |
| Green canopy cover at maturity | 0.0 | 0.0 |
| Total canopy cover at maturity (green and senesced) | 0.8 | 0.8 |
| Maximum canopy height (m) | 1.5 | 1.5 |
| Root parameters | | |
| Maximum root depth (m) | 1.7 | 2.00 |
| Root sensitivity to stress | 0.00 | 0.00 |
| Root length at emergence (cm) | 10 | 10 |
| Phenology parameters | | |
| Base temperature for development (°C) | 0 | 8 |
| Maximum temperature for development (°C) | 45 | 40 |
| Thermal time at emergence or fruit tree bud break (°C days) | 171 | 75 |
| Thermal time at flowering (°C days) | 2,141 | 700 |
| Thermal time at grain filling, root bulking or fruit growth (°C days) | 2,280 | 800 |
| Thermal time at physiological maturity or end of season (°C days) | 2,770 | 1,700 |
| Transpiration parameters | | |
| ET coefficient at complete canopy ground cover | 1.15 | 1.2 |
| Maximum water uptake (mm/day) | 10 | 12 |
| Crop name                      | Winter wheat | Grain corn |
|-------------------------------|--------------|------------|
| Leaf water potential at the onset of stomatal closure (J/kg) | −1,300       | −1,300     |
| Wilting leaf water potential (J/kg) | −1,600       | −1,600     |
| Canopy extinction coefficient for total solar radiation | 0.5          | 0.55       |
| Harvest parameters             |              |            |
| Unstressed harvest index       | 0.45         | 0.53       |
| Maximum fraction of carbon translocated to grains    | 0.25         | 0.2        |

**Data Availability Statement**

Data and code used for this study are available at http://doi.org/10.5281/zenodo.4477158 (Khanal et al., 2021).

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