Utilizing bioenergy crops to support transitions from irrigated agriculture and conserve the U.S. High Plains Aquifer

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Abstract

This study investigates the economic feasibility and groundwater implications of transitioning from irrigated corn production to alternative cropping systems such as sorghum and switchgrass—two common bioenergy feedstocks—across the High Plains Aquifer (HPA) region. The High Plains, heavily reliant on the Ogallala Aquifer, faces critical challenges due to unsustainable groundwater extraction exacerbated by climate and market conditions, leading to reduced irrigation capacities, diminished crop yields, lower land values, and escalating energy costs. Using a spatially explicit optimization framework combined with comprehensive economic and hydrogeological data, our analysis evaluates optimal land-use strategies and irrigation practices over a 30-year planning period. Results indicate significant regional variability in the economic viability of maintaining irrigated agriculture, driven by differences in aquifer recharge rates, groundwater availability, and market conditions. Nebraska and northern regions of Texas show sustained profitability from irrigated corn due to relatively favorable groundwater conditions and land rental costs, respectively. In contrast, many portions of Kansas and southern Texas face more likely transitions to dryland agriculture within two decades. Colorado and New Mexico show potential for significant adoption of switchgrass production as an alternative bioenergy crop. Overall, in 30 years we project approximately 23% of irrigated corn area across the HPA region to transition to dryland farming under business-as-usual. The study also reveals opportunities for producers to optimize their economic returns and biomass production potential, suggesting responsive stakeholder actions and/or policy planning could help sustain this region's agricultural production, aquifer life, and rural communities.

Keywords

Sustainable intensification

Groundwater depletion

Irrigation efficiency

Cropping system adaptation

Hydro-economic modeling

Land-use transitions

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CRediT authorship contribution statement

Karthik Ramaswamy: Writing – original draft, Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization. **Nazli Uludere Aragon:** Writing – review and editing, Validation, Supervision, Resources. **Tyler Lark:** Writing – review and editing, Supervision, Project administration, Funding acquisition.

1. Introduction

The agricultural sector faces mounting pressure from groundwater depletion, especially in regions that have historically depended on it for irrigation. With irrigation increasingly constrained by water availability, it is essential to identify sustainable alternatives that reduce water use while limiting the impacts on farm profitability. Research that investigates alternative cropping systems, optimized irrigation practices, and informed policy interventions is crucial for ensuring the long-term viability of agriculture in these regions and safeguarding the economic well-being of communities reliant on these vital water resources (Araya et al., 2019).

This challenge is particularly acute in the U.S. High Plains, where the Ogallala Aquifer, one the world's largest freshwater reserves, has supported decades of irrigated agriculture. Technological advances following World War II, including high-capacity wells and center pivot irrigation systems, led to widespread irrigation expansion (Hornbeck and Keskin, 2014). While these innovations enhanced productivity, they also accelerated the depletion of the Ogallala aquifer, a largely non-renewable resource in many parts of the region. With natural recharge rates often far below withdrawals rates, large sections of the central and southern High Plains now face severe declines in groundwater levels (Deines et al., 2020; Hornbeck and Keskin, 2014; Scanlon et al., 2012).

These hydrological trends have significant economic and ecological implications. Groundwater depletion has reduced well capacities, driven up energy costs for pumping, and lowered land values (Alley et al., 1999; Perez-Quesada et al., 2024; Sampson et al., 2019). In turn, agricultural producers are responding with various adaptation strategies including transitioning to dryland crops, switching to less water-intensive crops such as sorghum or wheat, converting land to pasture, or temporarily retiring fields through programs like the Conservation Reserve Program (Deines et al., 2020; Rao and Yang, 2010; Roberts and Lubowski, 2007; Wallander et al., 2013). In more severe cases, land has been permanently withdrawn from production altogether. These adaptive responses are grounded in observable long-term shifts in groundwater availability. For instance, (McGuire and Strauch, 2024) reported changes in groundwater well levels from the 1950s to 2019, ranging from a rise of 26.21 m (86 ft) in Nebraska to a decline of 80.77 m (265 ft) in Texas. The state-level weighted average change was estimated at -0.12 m (-0.4 ft) for Nebraska and -13.44 m (-44.1 ft) for Texas, revealing stark regional contrasts. These divergent trends illustrate the uneven aquifer depletion across the High Plains, indicating the need for locally-tuned strategies on resource management.

Yet, the High Plains region remains central to U.S. agriculture, both in terms of its contribution to national grain output and its role in supporting the livestock industry. The eight states overlying the HPA (Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming) comprise nearly 40% of U.S. agricultural lands, and about 32% of croplands (2022 figures from the USDA-NASS Agricultural Census). Notably, we estimate about 40% of the cultivated area in High Plains region relies on irrigation from the Ogallala aquifer (Xie et al., 2021). Among the main crops grown in the region (by area)—wheat, hay, corn, soybeans and to a lesser extent, cotton—corn emerges as the crop that has been most consistently cultivated under irrigation throughout the region (USDA-NASS, 2025).

To help mitigate water sustainability concerns, crops like switchgrass (*Panicum viragatum L.*) and biomass sorghum (*Sorghum bicolor (L.) Moench*) offer promising alternatives to irrigated corn in the region. Drought tolerant and with high biomass potential, these crops can serve as less water-intensive alternatives to irrigated corn. Switchgrass, a native perennial, is well suited to marginal and degraded lands and requires fewer inputs, making it ideal for sustainable energy production without competing with prime cropland (Abraha et al., 2016; Blanco-Canqui, 2016; Hamilton et al., 2015). Sorghum, meanwhile, offers familiarity to producers, shorter growing season, and competitive returns, particularly under declining well capacity (Cui et al., 2018; Ramaswamy, 2016; Warren et al., 2015).

Water sustainability is also a challenge for biofuel production, particularly when feedstocks are grown in heavily irrigated areas dependent upon nonrenewable groundwater resources (Chowdhury et al., 2025; Fingerman et al., 2010). Irrigated corn grown in the High Plains region contributes substantially to the nation's biofuel supply, and Nebraska is the second largest ethanol producing state. Thus, substituting irrigated corn with less water intensive alternatives could reduce the water footprint of supplied fuels, which currently consists of more than 80% corn-based ethanol (EIA Monthly Energy Review, Renewable Energy, Feb. 2024) processing 40% of the corn in the United States (USDA-ERS 2023).

This study evaluates the long-term economic viability of transitioning from irrigated corn – a high water use crop – to alternative, less water intensive crops that could also be utilized as bioenergy feedstocks under spatially variable groundwater constraints. Using an optimization framework that integrates spatially variable hydrological conditions and market dynamics, we estimate economically rational potential for biomass sorghum and switchgrass to replace currently irrigated corn areas in the High Plains Aquifer (HPA). We also model dryland corn as the leading competing dryland crop to more realistically capture overall transition dynamics. The objective is to identify the economic conditions and geographic contexts under which these crops emerge as a viable alternative to irrigated corn.

2. Materials and Methods

2.1 Approach

To assess and quantify the transitions from irrigated crop (corn) cultivation and the associated potential for bioenergy feedstock production over the HPA, we developed a spatially explicit optimization model. This model combines agronomic variables with hydrological ones related to irrigated fields' saturated thickness, hydraulic conductivity, and specific yield to assess the aquifer's potential to maintain irrigated agriculture, and the feasibility of transitioning to rainfed bioenergy feedstock cultivation at a point when irrigated agriculture becomes unsustainable. Our approach, illustrated in Fig. 1, comprises these key steps:

1. Data and Preprocess: Utilizing existing modeled data on aquifer and well characteristics to extrapolate current aquifer conditions in the study area.
2. Constructing an economic analysis to estimate the net returns under alternative irrigated (corn and sorghum) and non-irrigated (corn, sorghum and switchgrass) agricultural systems using an enterprise budgets approach.
3. Determining the optimal irrigated and non-irrigated crop choices across the HPA, subject to groundwater constraint, using a 30-year mixed integer linear programming (MILP) model.

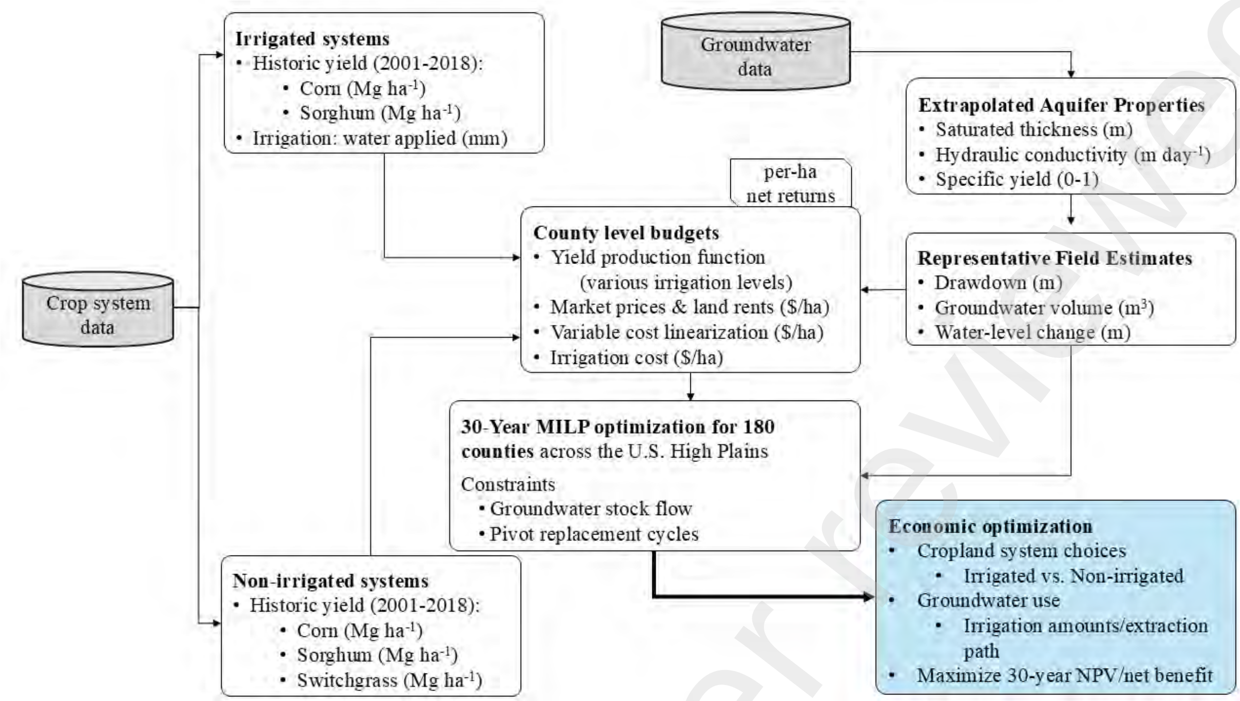


Fig. 1. Modeling approach and data integration. Multi-source data integration for optimizing agricultural systems, crop budgets, and aquifer dynamics. Assumptions are for a representative farm and groundwater availability.

2.2 County level data

The HPA spans parts of eight states - Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. This study builds upon the work of (Ramaswamy, 2024), which focused on groundwater-crop dynamics in five representative counties overlying the HPA. Expanding the spatial scope, the present analysis includes 180 counties across the HPA, while excluding peripheral counties with total areas under 100 km^2 and/or without irrigated land to maintain analytical relevance. County-level crop yield data (2000-2018) were sourced from the National Agricultural Statistics Service (NASS) of the US Department of Agriculture (USDA) for corn and sorghum. For our study, county-level average switchgrass yields were derived using spatially explicit yield projections from (Daly et al., 2018), which utilized PRISM climate data to simulate rainfed perennial grass productivity across the U.S. These gridded yield estimates were aggregated to the county level and reflect average dryland switchgrass productivity under typical climate conditions to provide a consistent, regionally appropriate benchmark for modeling biomass potential in non-irrigated systems. State average yields and prices are listed in Appendix A Table A.1 and Table A.2, respectively.

Where yield data was not available, particularly for sorghum, either district or state-level averages were used. Land rental rates were also obtained from NASS, and corn and sorghum prices (2018-2023) were collected from the USDA Agricultural Marketing Service. Direct production costs, including labor, insurance, fertilizer, seed, repairs, and interest were estimated using Kansas State University extension enterprise budgets (Kansas State University, 2024). Groundwater characteristics were derived from hydrogeologic parameters including saturated thickness and specific yield (McGuire et al., 2012), and permeability (Gleeson et al., 2014). Recent water level changes (2009-2019) were incorporated to refine estimates of saturated thickness over time. LANID irrigated field maps (2009-2017) from (Xie et al., 2021) were used to spatially identify and mask actively irrigated croplands within each county, allowing groundwater storage and pumping estimates to be constrained to areas under irrigation. Each of these spatially refined data layers were then aggregated to the county level to estimate total groundwater availability, potential pumping rates, and associated irrigation costs, which informed the characterization of representative irrigation cropping operation.

2.3 Representative farm and irrigated crop system characteristics

We consider a typical 48.6-ha (120-acre) field under center-pivot irrigation that draws from a groundwater well with a 31.5 L s^{-1} pumping capacity (Fig. 2). Field studies in the High Plains indicate that 457-559 mm (18-22 inches) of net water application typically suffice for irrigating corn, with variations arising from growing season length and planting and harvest dates (Klocke et al., 2011; Kranz et al., 2008; Trout and DeJonge, 2017). Using an assumed center pivot efficiency of 75% and application rates between 25.4-31.8 mm (1-1.25 in) per cycle, an irrigation capacity of 31.5 L s^{-1} can adequately meet crop water needs for corn over a typical irrigation period of 60-120 days (New and Fipps, 2000). We therefore chose 90 days to reflect typical corn (our baseline irrigated crop) and irrigated sorghum irrigated growing season.

To model baseline irrigation water use from groundwater resources (i.e. drawdown), we needed to estimate minimum saturated thickness per well. For wells operating at capacities of 6.3, 12.6, 18.9, 25.2, 31.5 L s^{-1} (100, 200, 300, 400, 500 GPM), this was calculated using a 90-day cone of depression, applying (Cooper and Jacob, 1946) and (Theis, 1935) equations. Given the heterogeneous aquifer properties and varying well depths, the saturated thickness was stratified into five layers, each representing minimum thickness requirements for different pumping capacities (Ramaswamy, 2016). This stratification enhances accuracy in assessing drawdown effects and extraction costs. Well interference effects were found to be negligible at distances greater than 0.4 km (0.25-mi), meaning that the drawdown caused by one well does not materially impact the performance of neighboring wells beyond this separation distance. This threshold was used to assume operational independence among wells in the modeling framework.

Groundwater availability also depends critically on specific yield, which describes the productivity of the aquifer, in volumetric terms, given aquifer properties. Here, it is calculated as the product of 64.7-ha (quarter section) x Porosity x Saturated Thickness. Porosity, reflecting the rock formation's storage capacity, ranges from 0% to 100% (Schloss et al., 2000). Our study assumes groundwater availability beneath a 64.7-ha land unit, of which 48.6-ha are irrigated. This reflects the standard footprint of a center-pivot irrigation system, which typically irrigates a circular area covering approximately 75% of a quarter section (Dieter et al., 2018; Lamm et al., 2015). The remaining area includes infrastructure or non-irrigated buffer zones. While this approach simplifies heterogeneity at the county level, it provides tractable and spatially consistent unit for simulating irrigation decisions and groundwater use. To approximate county-wide dynamics, we scale this representative field structure to reflect average conditions, recognizing that irrigated area generally comprises about 40% of total cropland across the High Plains (USDA-NASS, 2022).

The 2009 USGS spatial dataset of saturated thickness and water-level changes since predevelopment served as baseline. This dataset was updated using biannual water-level change data through 2017 (McGuire and Strauch, 2022). Using these maps of groundwater characteristics (permeability, porosity, and water level changes). we derived county-level averages of well depth and water-level change with GIS approaches (zonal statistics) to estimate effective well capacity (Fig. 3a-3b).

We initialized hydrogeologic conditions using USGS 2009 spatial dataset of saturated thickness and water-level change since predevelopment as the baseline (McGuire et al., 2012). We then time-updated this based to 2017 by applying USGS biannual (2009-2017) water-level change grids (McGuire, 2017, 2014, 2013; McGuire and Strauch, 2024) to produce a 2017 saturated thickness surface. To align with actively irrigated lands, we masked the updated saturated thickness using LANID for 2017 (Xie et al., 2021) and extended the computations through 2024 using average (2009-2017) water-level change to estimate the effective saturated thickness. County-level metrics were then calculated using zonal statistics, yielding irrigated-area-weighted averages of saturated thickness and water level changes (to determine the declining or recharging zones) for each county.

Hydraulic parameterization combined (i) specific yield/porosity from USGS products (McGuire et al., 2012), and (ii) permeability/hydraulic conductivity from the GHYMPS database (Gleeson et al., 2014). Using these parameters with the irrigated area weighted effective saturated thickness, we classified sustainable well capacities drawdown for 6.3, 12.6, …, 31.5 L s^{-1} with approximately 9 m (~30 ft) as safety zone at the bottom of the aquifer. To be consistent with the prior work, we excluded pixels with saturated thickness < 9.1 m as operationally unstainable for center-pivot irrigation (Deines et al., 2020; Haacker et al., 2016; Hecox et al., 2002).

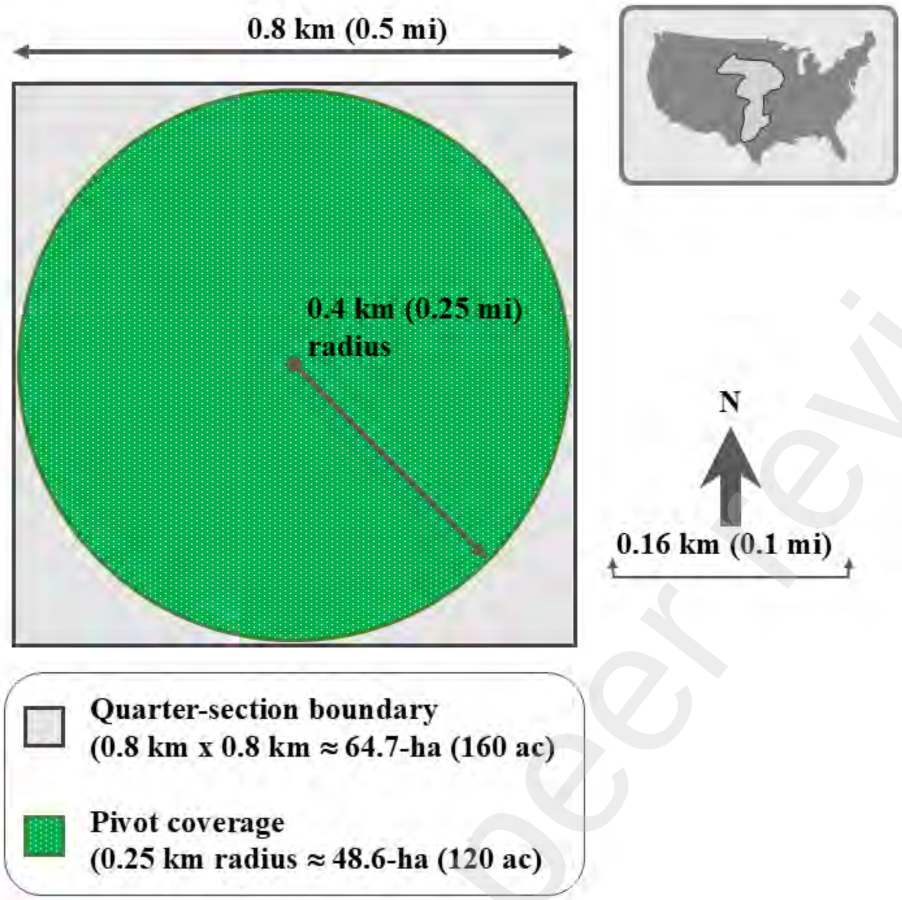


Fig. 2. Illustrates a typical farm field in the High Plains Aquifer region, showcasing a center pivot irrigation system on a 48.6-ha field within a quarter section (64.7-ha).

a) **b)**

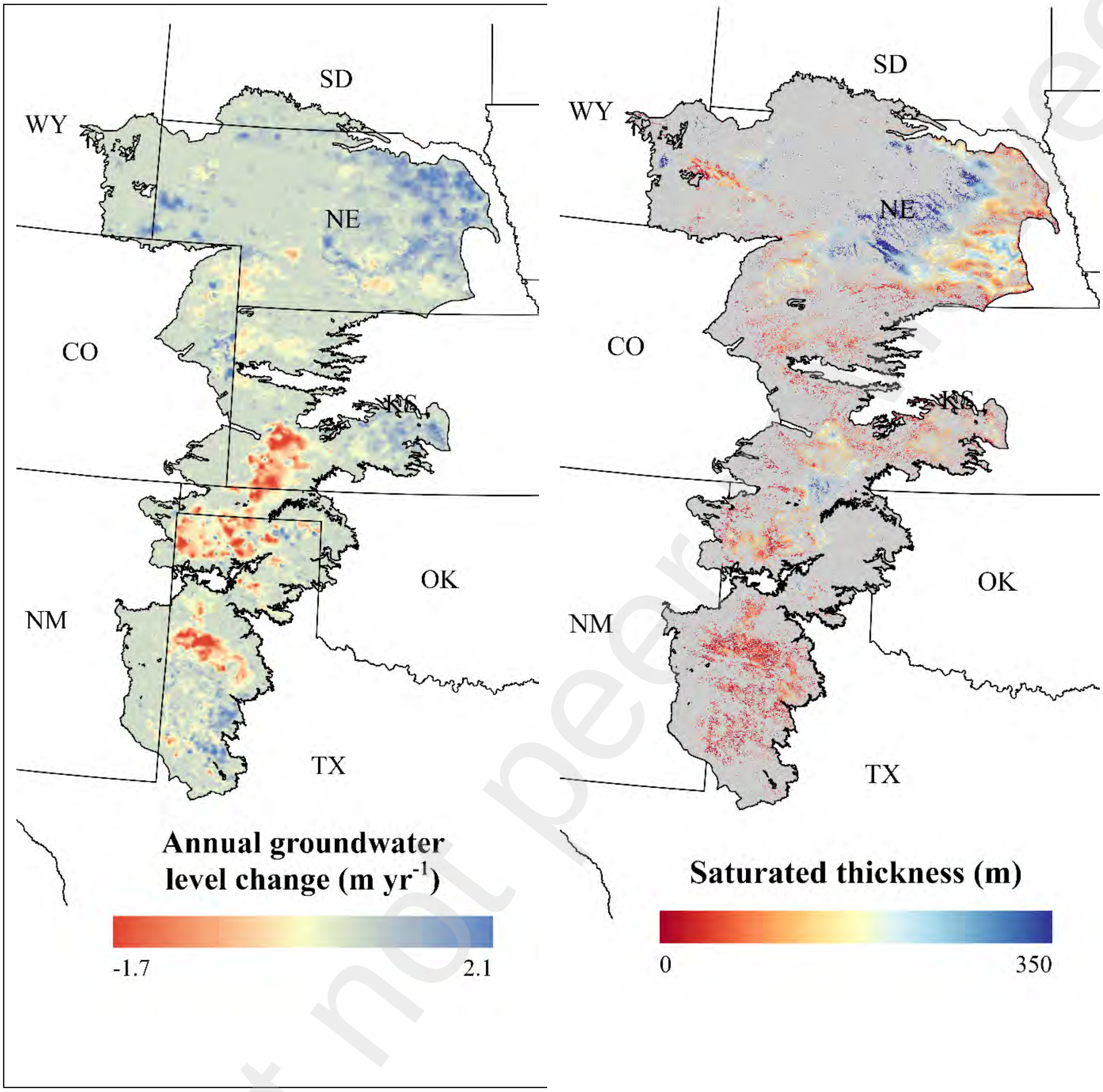


Fig. 3. Spatial variation in groundwater conditions across the U.S. High Plains Aquifer. a) mean rate of groundwater levels change from 2009 to 2024 based on (McGuire and Strauch, 2024), b) estimated aquifer thickness within irrigated areas as of 2024, representing available groundwater storage used in this study.

2.4 Economic Analysis

Our economic analysis consists of two major steps: (1) developing crop budgets for each agricultural system for 180 HPA counties for irrigated corn, irrigated sorghum, non-irrigated corn, non-irrigated sorghum and switchgrass (resulting in 900 budgets), and (2) constructing individual county-specific 30-year MILP models to determine the optimal cropland system choices, groundwater use , and net present value (NPV) for a representative field by HPA county. The production value of the irrigated lands is determined by finding the optimal extraction path (annual withdrawal amount from the aquifer) of limited groundwater for irrigation of corn and grain sorghum based on the concept of "User Cost," which represents the potential future profits lost due to current resource use (Dasgupta and Heal, 1979; Hotelling, 1931; Stoecker et al., 1985; Vaux, 2011). Our overall aim is to maximize total profits over the life of the aquifer based on the theoretical framework in Appendix B.

We developed representative crop budgets for irrigated (corn and sorghum) and non-irrigated (corn, sorghum, and switchgrass) production systems as follows.

1. To estimate irrigated crop yields for different well capacities, we began with county-level yield averages from USDA NASS, which we assumed to reflect production under relatively unconstrained irrigation conditions approximated here as 31.5 L s^{-1} well capacity. This means the crops receive sufficient water to meet their full evapotranspiration needs throughout the growing season.
2. Next, following the (Lamm et al., 2007) study, we determine the yield response for irrigated corn and sorghum to well capacities from 6.3 L s^{-1} to 25.2 L s^{-1} in increments of 6.3 L s^{-1} based on possible water application using pivot irrigation frequency during growing season, which is a key factor in our economic analysis. Then using the relative yield response

identified the irrigation to be applied for well capacities 6.3, 12.6, …, 31.5 L s^{-1} following (Klocke et al., 2011) for corn and (Klocke et al., 2012) for sorghum, focusing on western Kansas. Well capacity influences crop yields because higher capacities allow for more irrigation, potentially leading to higher yields, especially during periods of peak water demand (Irmak S., 2015; Klocke et al., 2012, 2011; Rudnick et al., 2019; Trout and DeJonge, 2017).

3. The predicted yields were then used to estimate relative irrigation amounts using numerical methods (Abramowitz and Stegun, 1964). We used the same response function for all HPA counties due to lack of recently available studies from other parts of the HPA.

Predicted irrigated yields of corn and sorghum (under varying well capacities) could deviate from the observed responses due to differences in soil, climate, or management practices between counties in western Kansas and other parts of the HPA. Nevertheless, we expect our use of a universal yield response to be acceptable as any small county level variations in yield response relationships are likely to be mitigated when averaged across the regional scale of our analysis.

Several key assumptions underpin the MILP portion of our economic analysis. First, our model uses a 30-year planning horizon to evaluate crop choices, irrigated and non-irrigated area, and biomass production. Next, consistent with other economic studies, we rely on the "single-cell aquifer" hydrological representation to model temporal allocation of the groundwater. Simply put, the aquifer is assumed to be spatially homogeneous within the unit of analysis (48.6-ha field). Although aquifer properties, well depth and drawdown (cone of depression) that limits the extraction capacity can vary widely in space, this simplification is necessary because there is currently inadequate information to capture the heterogeneity at the irrigated field level for modeling purposes (Bredehoeft and Young, 1970; Brozović et al., 2010; Gisser and Mercado, 1972; Wheeler et al., 2008).

The overall objective of the MILP is to maximize the NPV of the farming operation (per field) over the 30-year planning horizon. The model optimizes over crop selection, irrigation amount, and timing of pivot investment subject to constraints on water availability, land availability, and capital costs. Existing research often treats irrigation investment costs either solely as variable operating expense or as levelized costs that amortize capital expenditures over the system's expected life (Lamm et al., 2015; O'Brien et al., 1998). While this approach simplifies economic modeling at the per unit of land level, it may obscure important real-world constraints. In practice, irrigation systems typically require substantial upfront capital investment – costs that are indivisible or lumpy that producers must commit the full investment before irrigating any portion of the land. These poses a critical barrier, especially where financing is limited or unavailable (Frisvold and Deva, 2012; Morris and Persons, 2019). By modeling irrigation investment as a discrete capital investment rather than a smoothly scalable cost, our framework better reflects adoption realities and the nonlinear nature of irrigation expansion decisions under capital constraints.

The MILP model considers a binary "go / no-go" decision (see Eq. 2.1) representing the initial investment decision to establish irrigated production through center pivot irrigation systems at the outset of the planning horizon. $\in \{0,1\}$

This binary decision explicitly captures the strategic choice faced by landowners—whether to incur the fixed initial investment costs associated with pivot installation, thereby committing to subsequent years of irrigated cropping under increasing uncertainty of available groundwater resources, or foregoing irrigation investments altogether. The binary choice differentiates between county-level irrigated fields that are viable under long-term groundwater constraints and those that are not.

In this analysis, the decision to install a pivot system happens at the beginning of the planning period. This methodological choice distinguishes long-term optimal investment strategies from economically suboptimal or unsustainable alternatives. For this analysis, all county-field units start with new pivot systems that are purchased at the outset of the project. This assumption facilitates a comparison of long-term economic benefits, crop management strategies, and water use efficiency, controlling for initial infrastructure conditions. It also simplifies economic calculations by avoiding the need to make assumptions of remaining economic life for existing irrigation systems in the HPA, for which reliable data are lacking.

A typical center pivot system has a lifespan of approximately 15 years, which constrains the model to allow for a maximum of two full investment cycles over the 30-year period simulation period. Sensitivity testing conducted outside the scope of this paper suggests that introducing additional investment cycles has little impact on the model's long-term outcome. This insensitivity is primarily due to the dominant role of structural constraints, namely limited groundwater availability, and declining marginal returns to crop productivity under irrigation, which exert greater influence on long-run economic decision-making than the specific timing or frequency of the infrastructure renewal.

When it is time to replace the pivots in year 16, the model evaluated whether to invest in a new pivot system and continue irrigated production for an additional 15 years, or to transition to a dryland cropping system, depending on which option yields the highest net returns. The transition to dryland farming is modeled as a gradual process based on remaining groundwater – fields begin to reduce irrigated area as well capacity decline due to falling well capacities, eventually resulting in a full conversion to dryland crops when groundwater becomes insufficient to support continued irrigation investment.

The net present value is calculated using an annual discount rate of 7 percent. The cost of replacing the center pivot is assumed US$75,000 (real terms) per field with a typical lifespan of 15 years (Lamm et al., 2015; Reynolds et al., 2020).

The MILP profit maximization objective function used in this analysis is succinctly defined as,

$$\max_{\mathbf{x} \in \mathbb{R}_+^n, \mathbf{y} \in \mathbb{Z}^m} f(x,y) = \mathbf{OBJ}^{\mathrm{T}}\mathbf{x} + \mathbf{PC}^{\mathrm{T}}\mathbf{y}, \tag{2.1}$$

$$\mathbf{x} \geq \mathbf{0}, \mathbf{y} \in \mathbb{Z}^m, \tag{2.2}$$

$$A\,\mathbf{x} + P\,\mathbf{y} \leq \mathbf{b}. \tag{2.3}$$

where, $\mathbf{x} \in \mathbb{R}_+^n$ are the continuous variables of crop choices, $\mathbf{y} \in \mathbb{Z}^m$ are the integer variable for pivot investments, $\mathbf{OBJ}$ components represent the profits associated with $\mathbf{x}$, and $\mathbf{PC}$ are the components corresponding to the cost of pivot investment related to integer variable **y**. A comprehensive explanation of the MILP model and parameters is provided in Appendix C.

Unless explicitly noted otherwise, all results and reported outcomes represent the 30-year modeling period and are relative to the baseline of irrigated cropland area, which we assume to be under corn (or corn rotation) cultivation.

3. Results

We assessed the baseline production system of conventional irrigated corn against alternative cropping systems of sorghum and switchgrass and identify economic and hydrological conditions under which transitions between the crop systems are viable.

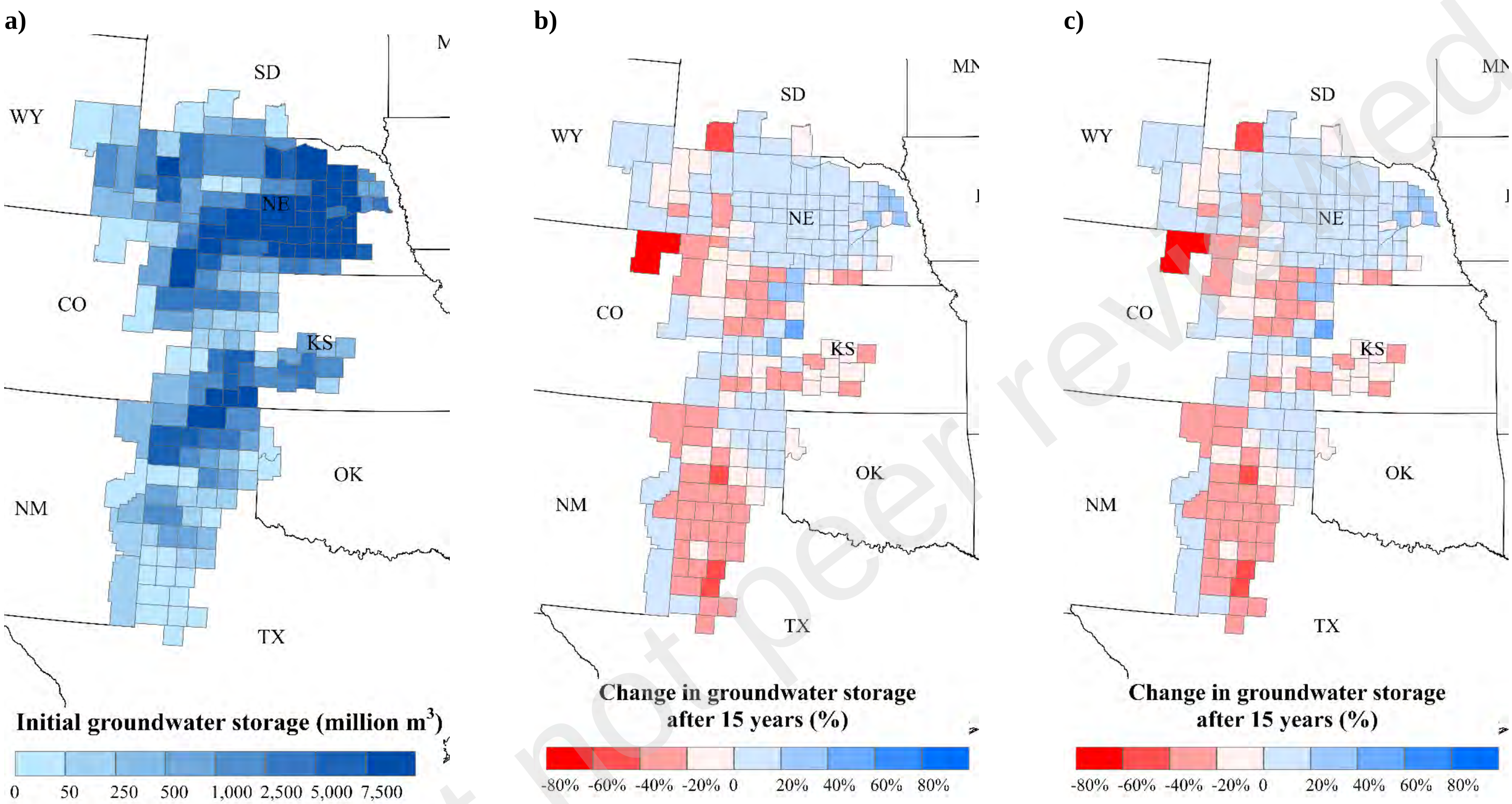
We find that transitions away from irrigated agriculture emerged once the marginal value of irrigated production no longer covered the associated costs of the inputs, including production, pivot investment, and groundwater extraction. This outcome was contingent on three conditions, (i) reduced groundwater availability that limits investment for irrigated production, (ii) diminishing marginal productivity due to deficit water application to crops, and (iii) increase in extraction cost. We first examine results for projected changes in groundwater availability and subsequently assess the implications for crop transitions, biomass production, and bioenergy feedstock potential.

3.1 Groundwater levels trend in irrigated croplands

The spatial variation in both groundwater endowments and depletion pathways across the High Plains shapes the timing and extent of irrigation transitions over time. Modeled aquifer volumes at the beginning and end of the simulation period reveal substantial differences across states and sub-regions. Fig. 4a-4c illustrate the spatial variability in aquifer volumes per hectare across the High Plains at the beginning (Fig. 4a), reinvestment period (Fig. 4b) and at the conclusion at the 30-year simulation period (Fig. 4c). These differences reflect underlying heterogeneities in initial storage levels, extraction intensities, and local recharge dynamics, which together determine the path and direction of depletion.

Initially, aquifer volumes exhibit notable regional variability with the highest groundwater availability concentrated predominantly in central and northern Nebraska with approximately 683.45 km^3. Moderate groundwater reserves were observed in Kansas (90.14 km^3), Texas (40.56 km^3) and Colorado (31.33 km^3).By the conclusion of the simulation period, substantial groundwater depletion occurs throughout much of the region. Texas experiences the most pronounced depletion, retaining roughly 41.1% (16.69 km^3) of its initial groundwater volume, reflecting intensive groundwater extraction pressures and minimal recharge rates. Nebraska, however, demonstrates greater aquifer sustainability, maintaining about 77.8% (532.00 km^3) of its initial groundwater storage, attributable to initial high groundwater availability and favorable recharge conditions. The lowest depletion rates were observed in Kansas and Colorado, retaining approximately 50.4% (45.47 km^3) and 42.5% (13.31 km^3) of their initial volumes, respectively, highlighting regional variations in groundwater extraction and recharge dynamics.

Compared to other states, South Dakota and Wyoming exhibited relatively stable aquifer conditions, retaining 78.4% (0.8 km^3) and 74.4% (2.94 km^3) of their respective groundwater volumes by year 30, reflecting their limited irrigation intensity. Oklahoma maintained moderate groundwater sustainability, with 69.3% (9.85 km^3) of its initial volume remaining, whereas New Mexico retains 58.6% (0.49 km^3), indicating depleting rates despite its lower aquifer capacity. Collectively, these findings underscore the need for region-specific management strategies tailored to unique hydrogeological and economic contexts, to ensure the long-term sustainability of irrigated agriculture in the High Plains region.



1 **Fig. 4. Spatiotemporal dynamics of groundwater storage across the High Plains Aquifer during the 30-year simulation period. a) Initial**

2 **aquifer storage volume (m^3) within irrigated corn area at the beginning of the simulation period, b) Relative change in storage after 15 years**

3 **(%), normalized to initial volume, c) Relative change after 30 years (%), normalized to initial volume.**

3.2 Well capacities and transitions to dryland production

We estimate 683,919 hectares (1.69 million acres)of cropland is likely to transition from irrigated to dryland agricultural production in the US HPA over the 30-year simulation period(Fig. 5). This represents 23% of the currently irrigated corn area of 2.97 million hectares (7.33 million acres) in the region. The year of dryland transition and remaining aquifer during transition is shown in Fig. 5a and Fig. 5b, respectively.

At the beginning of the simulation, 89% of irrigated area (2.64 million hectares) is supported by 31.5 L s^{-1} systems, 3% is supported by 25.2 L s^{-1}, 1.6% by 18.9 L s^{-1}, and 0.8% by 12.6 L s^{-1}, and the remaining 5.5% of the irrigated areas is insufficient to support sustained pumping and transitions to dryland. By the reinvestment point, the share of irrigated area at 31.5 L s^{-1} wells decreases to 75.3%, while area at 18.9 L s^{-1} (0.9%) and 12.6 L s^{-1} (0.4%) begins to decrease, and insufficiently supplied (i.e. dryland) areas expands to 23.1%. By year 30, the system settles to a new equilibrium characterized by fewer 31.5 L s^{-1} wells (65.8%), while dryland remains essentially unchanged at 23.1%, and 6.3 L s^{-1} systems are negligible (Fig. 7).

For Nebraska, model results indicate that out of 1.88 million irrigated corn hectares approximately 79.37% are projected to remain under irrigated production throughout the 30-year period. An estimated 6.07% of this area is economically favorable to transition to dryland production, based on marginal returns from initial pivot investment cost. At the time of pivot reinvestment, a further 14.56% of the irrigated corn area is expected to shift to dryland agricultural systems. Across Nebraska, most irrigated counties maintain high-capacity wells – roughly 1.46 million irrigated corn hectares operate at ≥31.5 L s^{-1}, supported by approximately

579.96 million m^3 of groundwater stock and consistent recharge of 17.32 million m^3. In contrast, five counties in northeastern Nebraska appear to be economically well-positioned to adopt non-irrigated (dryland) agriculture due to their high non-irrigated yields and low porosity, which restricts groundwater pumping.

Over the course of the simulation period, Kansas exhibits a clear trajectory of groundwater depletion and corresponding adjustments in irrigation practices. At the initial stage, approximately 85.32% of the 0.5 million hectares of irrigated corn is supported by high-capacity wells (31.5 L s^{-1}), while an additional 4.73% and 2.94% fall under the 25.2 and 12.6 L s^{-1} categories. At pivot reinvestment point, the share of the high-capacity wells (31.5 L s^{-1}) declines substantially to 69.8%, indicating a reduction in available groundwater for intensive irrigation. Simultaneously, 3.69% of irrigated area is supplied by 18.9 L s^{-1} and 0.53% by 12.6 L s^{-1}, while the remaining 25.95% shifts to dryland production. By the end of the simulation, the share of dryland agriculture stabilizes around 26%. However, the irrigated acreage supported by 31.5 L s^{-1} wells decreases further in absolute terms, while reliance on lower-capacity wells (18.9 and 12.6 L s^{-1}) becomes more prominent, 8.7% and 17.3%, respectively.

Texas also undergoes a marked transition in irrigation in terms of utilized well capacities. At the beginning of the simulation, the majority (68.26%) of irrigated corn cropland of 0.30 million hectares in Texas is supported by high-capacity wells (31.5 L s^{-1}), while 18.28% and 12.62% operate under 25.2 L s^{-1} and 18.9 L s^{-1} conditions, respectively. Only a negligible share of land falls under the 12.6 L s^{-1} category (0.83%), and dryland agriculture is virtually absent. By the pivot reinvestment stage, these patterns begin to shift. The share of land with 31.5 L s^{-1} well capacity declines to 54.41%. While 18.9 L s^{-1} well-supported irrigated area grows to 2.3%, the most notable change is the sharp increase in dryland cropland, which now constitutes 43.3% of the total area. At the conclusion of the simulation, these trends are further accentuated. Only 16.07% of Texas's irrigated cropland remain supported by 31.5 L s^{-1} wells, and a large portion shift to using lower-capacity wells: 10.67% at 25.2 L s^{-1}, 14.64% at 18.9 L s^{-1}, 15% at 12.6 L s^{-1}, and dryland agriculture at 43.51% at the end of the simulation period.

At baseline, Colorado's irrigated area (0.19 million hectares) is dominated by high-capacity wells, 90.3% at 31.5 L s^{-1}, and 8.42% already in dryland. By the investment point, the 31.5 L s^{-1} share declines to 85.6% and dryland edges up to 9.47%. By year 30, well capacity degrades further – 80.9% of the total area remains at31.5 L s^{-1}, while 9.4% operates at12.6 L s^{-1}, 0.20% at 6.3 L s^{-1}, and dryland stays near 9.5%. Oklahoma begins with 81.7% of irrigated area at 31.5 L s^{-1} (40,947 hectares of 50,126 hectares total) and 18.3% at25.2 L s^{-1}, with no dryland. At the reinvestment point through the end of simulation period, the 18.3% of 25.2 L s^{-1} declines to12.6 L s^{-1}, while the 31.5 L s^{-1} share is unchanged. New Mexico starts with a small irrigated base (17,464 hectares) and only 11.5% is supported by31.5 L s^{-1}, while 32.6% and 41.5% operate at 18.9 L s^{-1} and12.6 L s^{-1}, respectively; 14.3% is already dryland. By the reinvestment stage, the state fully exits irrigation with 100% dryland production. This pattern persists through year 30.

All in all, across the High Plains region, the simulation reveals a progressive decline in irrigation capacity over the 30-year planning period, marked by shifts in utilizing wells at higher pumping capacities to lower-capacity systems and eventually, to dryland agriculture. The proportion of cropland for agricultural systems share and aquifer life is shown in Fig. 6.

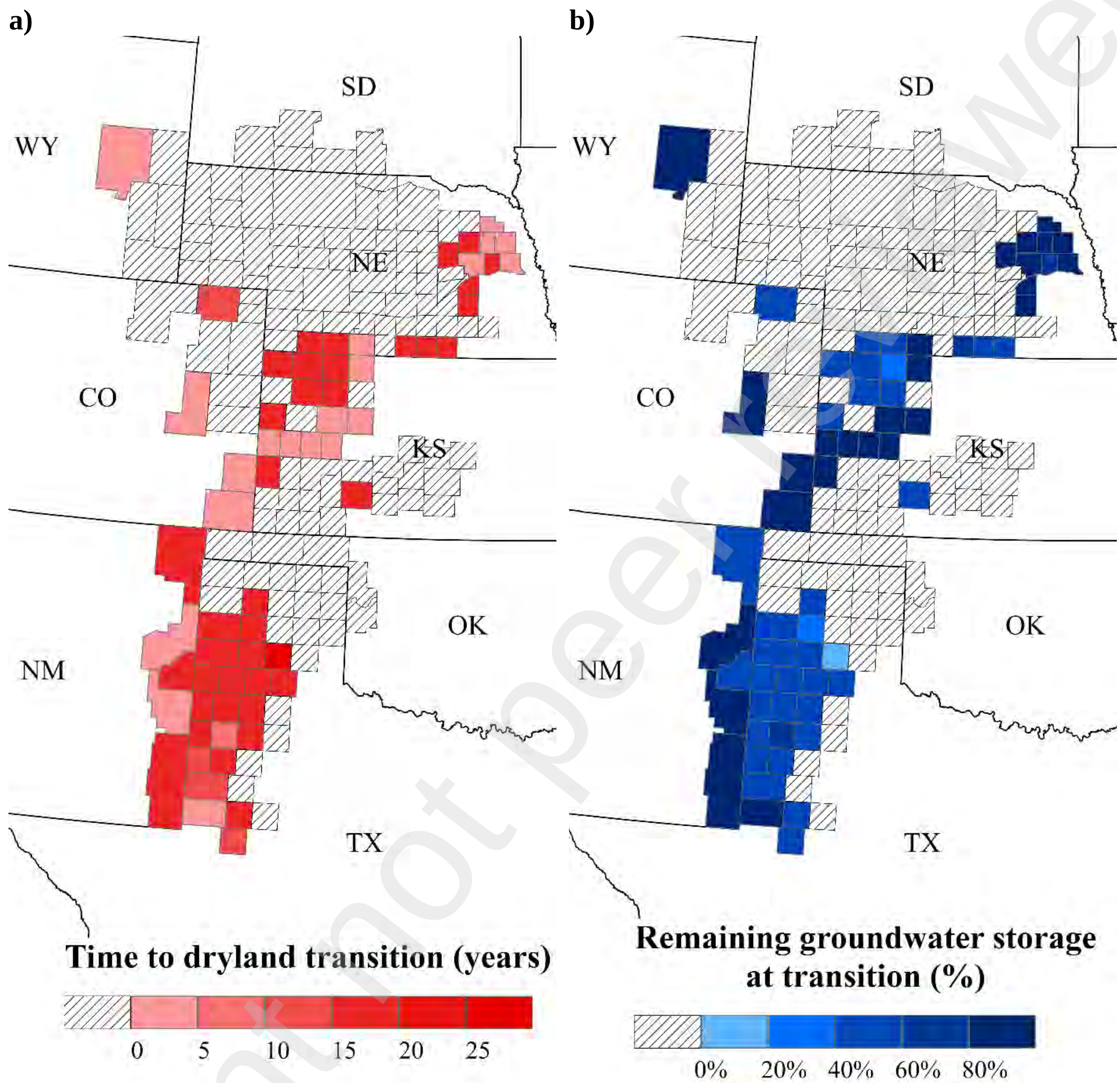


Fig. 5. Spatiotemporal transition from irrigated to dryland production across the U.S. High Plains Aquifer region. a) Estimated number of years until irrigated corn production becomes economically or hydrologically infeasible, b) Fraction of initial aquifer storage remaining at the time of transition. Cross-hatched counties denote no transition during 30-years period.

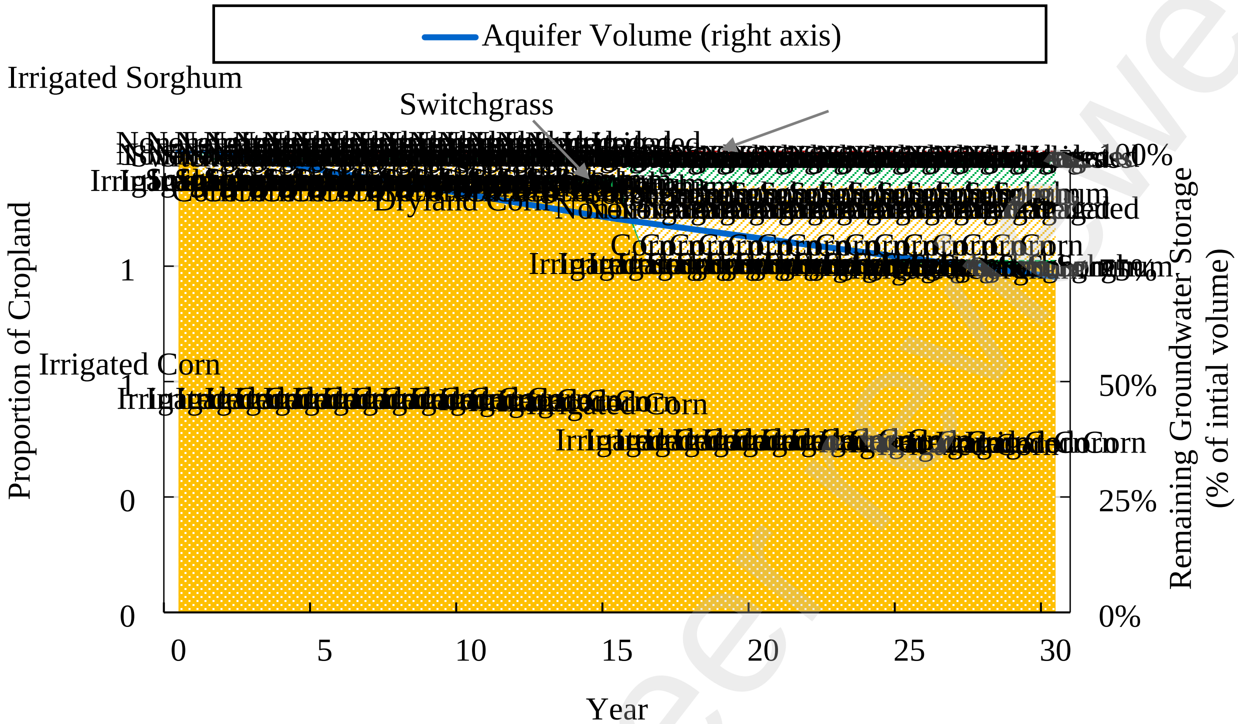


Fig. 6. Temporal evolution of crop composition and aquifer volume over a 30-year simulation period across the U.S. High Plains Aquifer. The stacked area shows the proportion of cropland allocated to irrigated and dryland crops, including sorghum, and switchgrass. The blue line (right axis) represents the remaining aquifer storage as a percentage of its initial volume, illustrating the coupled dynamics between declining groundwater availability and crop systems transitions.

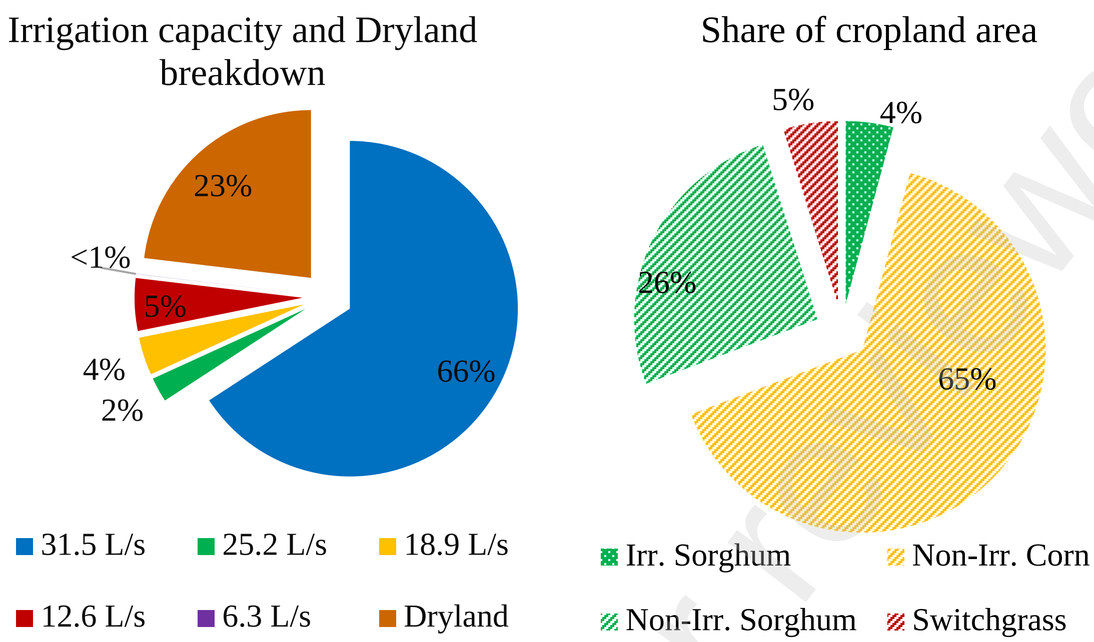


Fig. 7. Land use transition and irrigation distribution across the U.S. high Plains following irrigated corn phase-out. a) Distribution of cropland area by well capacity class (L s^{-1} or L/s) and total dryland extent after 30 years, b) Proportion of land allocated to major crop types following the decline of irrigated corn.

3.3 Biomass Production, Specific Crop Shifts, and Economic Impacts

Through the simulation period, irrigated corn production in the HPA region decreases by 3.9% by Year 15 and by 21.9% by Year 30, falling from an estimated 30.8 Mt yr^{-1} (million tonnes per year) to 24.1 Mt yr^{-1}(and yields changing from 11.0 Mg ha^{-1} (163.5 bu ac^{-1}) to 10.8 Mg ha^{-1} (160.2 bu ac^{-1}), on average) as the economic viability of center-pivot irrigation wanes. The total biomass production and total net returns over the period of 30 years is shown in Fig. 8a and Fig. 8b, respectively.

Different state-level trajectories constitute this aggregate trend. Kansas, a major irrigated corn producing state at onset with 5.2 Mt yr^{-1}, exhibits the sharpest long-term contraction, with annual output declining by 32.4% to 3.5 Mt yr^{-1} by Year 30. Texas follows a similar pattern, with irrigated corn production halving from 3.37 Mt yr^{-1} to 1.68 Mt yr^{-1}per year. Our simulations suggest a complete phaseout of irrigated corn by Year 30 in New Mexico, illustrating the unsustainability of irrigated agriculture where the aquifer is shallow and recharge is limited. Even Nebraska, perceived as more hydrologically buffered, witnesses a 15.7 % decline in irrigated corn output, from 19.5 Mt yr^{-1} to 16.4 Mt yr^{-1}. Irrigated corn output also declines in Oklahoma (18%), South Dakota (0.5%), and Wyoming (6.7%).

3.3.1 *Irrigated Corn Replacement by Irrigated Sorghum*

In response, irrigated sorghum takes on a transitional role during the first 15 years of the simulation under declining irrigation capacity. Starting from an initially negligible base of 10,166 t yr^{-1} (tonnes per year) of production per year, irrigated sorghum production surges to 374,458 t yr^{-1} by Year 15 – a 35-fold increase before settling to 166,563 t yr^{-1} by Year 30.

State-level analysis reinforces this interpretation. Kansas drives much of the early expansion, with irrigated sorghum rising from 10,166 t yr^{-1} to 172,846 t yr^{-1} Year 15, before declining to 93,590 t yr^{-1} by Year 30, net gain of 820%. Texas exhibits a similar pattern from zero production in Year 1 to 201,590 t yr^{-1} in Year 15 but declining to 26,747 t yr^{-1} by Year 30. Oklahoma emerges as a new entrant into irrigated sorghum production in the final period, producing 46,205 t yr^{-1} by Year 30, despite no prior production.

These results demonstrate the adaptive but temporary utility of sorghum under moderate groundwater stress, where partial pivot capacity remains but high-demand crops such as corn are no longer viable. The eventual decline of irrigated sorghum by Year 30 signals that even water-efficient irrigated crops are unsustainable in regions where aquifer depletion becomes severe or reinvestment costs rise above profit margins.

3.3.2 *Replacement by Non-Irrigated Corn and Non-Irrigated Sorghum*

Non-irrigated corn is projected to increase in the region by 283.8%, from 835,532 t yr^{-1} to 3.2 Mt yr^{-1}, while non-irrigated sorghum grows by 288.7%, from 196,861 t yr^{-1} to 765,176 t yr^{-1}. These shifts represent a reconfiguration of agricultural systems toward dryland practices, driven by both physical constraints and economic adaptation.

Nebraska leads this transition, with non-irrigated corn production expected to rise from 835,491 t yr^{-1} to over 2.59 Mt yr^{-1} by Year 30 – a 210.9% increase. Kansas mirrors this shift with non-irrigated sorghum increasing more than fourfold, from 137,195 t yr^{-1} to 559,233 t yr^{-1}. Notably, Texas exhibits the most dramatic expansion in non-irrigated corn, growing from a negligible 42 t yr^{-1} to over 609,000 t yr^{-1} by year 30, suggesting that significant portions of previously irrigated area are likely to transition permanently to dryland agriculture.

3.3.3 *Replacement by Switchgrass*

Across all states, switchgrass production increases by 35.4%, from 296,260 t yr^{-1} to 401,120 t yr^{-1} over the 30-year period. Although absolute values are modest compared to corn, the growth trajectory suggests that switchgrass is being adopted selectively in areas where neither corn nor sorghum is viable or profitable. Colorado and New Mexico show particularly strong potential. In New Mexico, switchgrass could expand more than six-fold from 16,485 t yr^{-1} to 120,367 t yr^{-1} per year, replacing irrigated corn systems phased out by Year 30. Colorado maintains stable switchgrass production, increasing by 12.9% by Year 15 and retaining this level through Year 30. Annual biomass output increases from 100,792 t yr^{-1} to 113,792 t yr^{-1}.

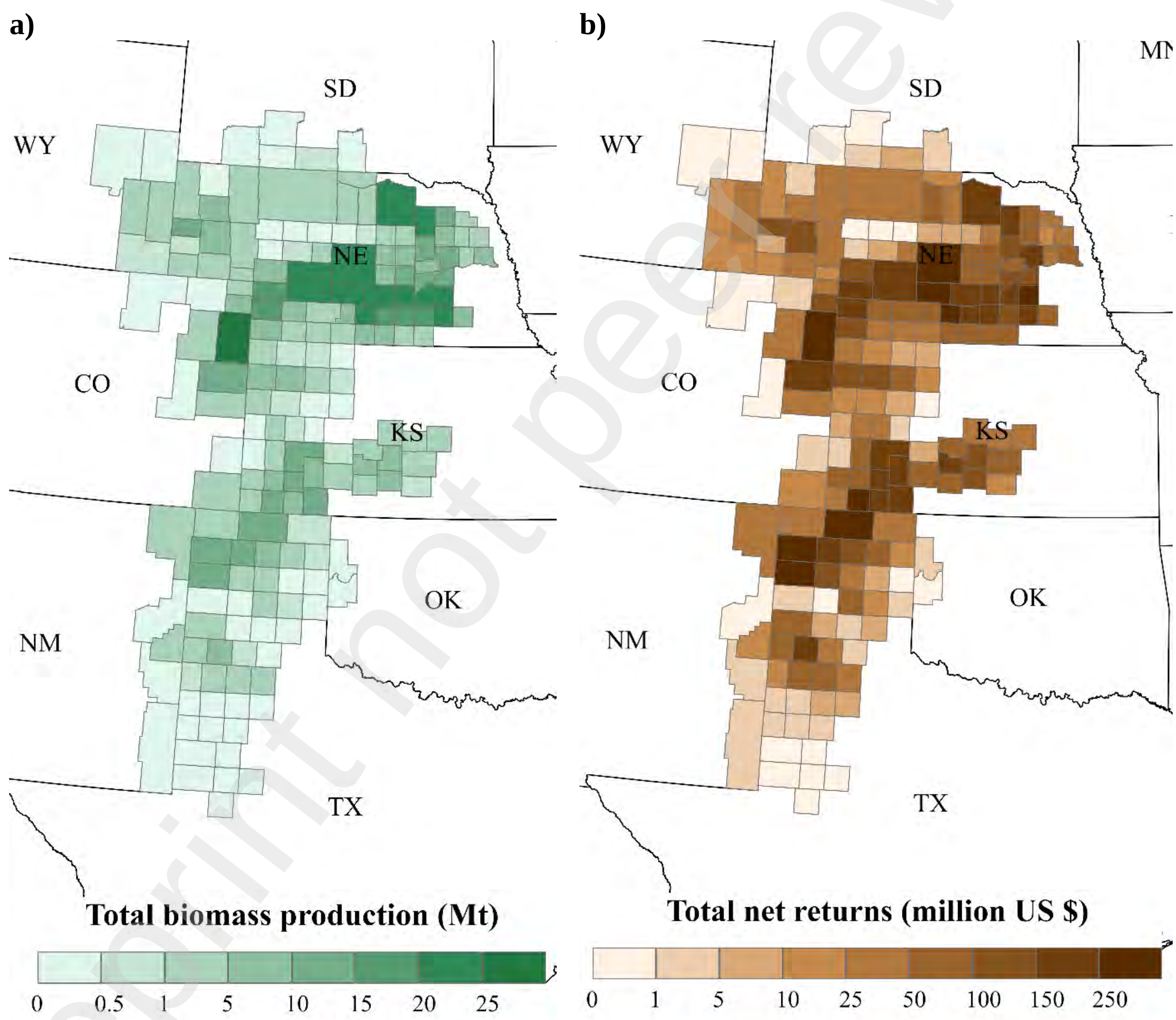


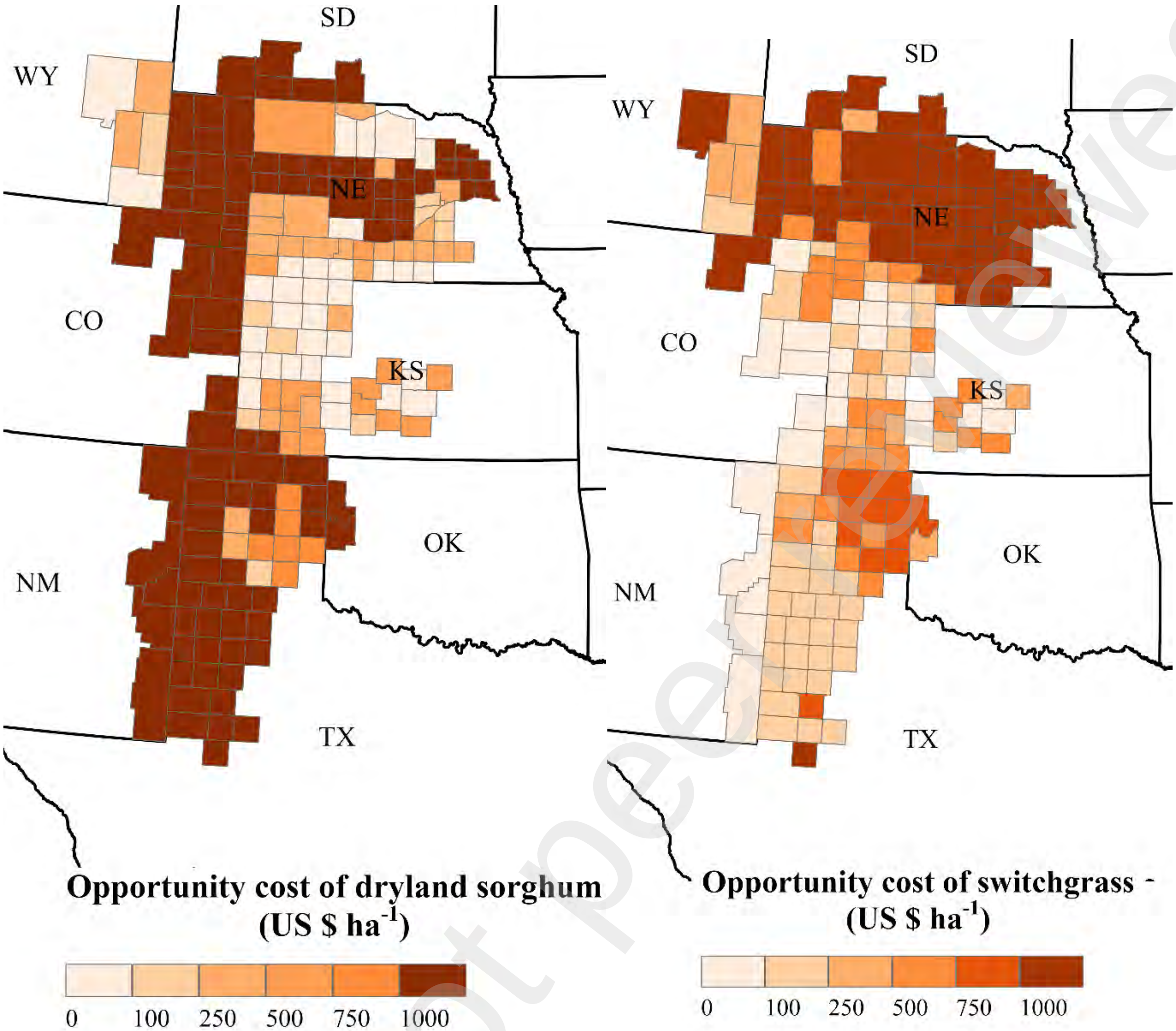
Fig. 8. Spatial distribution of total economic benefits from bioenergy crop production across the U.S. High Plains Aquifer during the 30-year simulation period. a) Cumulative biomass output from all modeled feedstocks over the planning horizon, b) Aggregated net present value (NPV) reflecting the spatial variability in profitability driven by groundwater availability and crop productivity.

3.4 Opportunities for bioenergy feedstocks

The economically viable potential for producing dryland sorghum exhibits a clear north-south gradient (Fig. 9a). Central and northern portions of Nebraska, northern Colorado, and parts of Wyoming exhibit the lowest opportunities cost up to \$247 ha^{-1} (\$100 ac^{-1}), indicating favorable conditions for dryland adoption. In these regions, the marginal cost of abandoning irrigation is small, and in some cases, dryland sorghum may already be economically competitive with irrigated corn. In contrast, western and southern Kansas, the Texas Panhandle, eastern New Mexico, and the majority of Oklahoma display a high opportunity cost exceeding \$865 ha^{-1}. Many counties in Texas High Plains (e.g., Carson, Donley, Gray, Lipscomb, and Wheeler Counties) exceed \$741-\$988 ha^{-1} in estimated opportunity cost, signaling that dryland sorghum adoption would be uncompetitive under current conditions without substantial policy incentives or greater shift in input/output prices. Central Kansas offers a transitional zone, with mixed opportunity cost (\$247-741 ha^{-1}), reflecting moderate yield potential and variable irrigation dependencies. Several counties such as Scott County and Graham County demonstrate opportunity costs between \$494 ha^{-1} and \$618 ha^{-1}, suggesting partial economic viability that may become favorable with modest change in policy, market prices, and technology adoption.

In contrast to sorghum, the opportunity cost of adopting switchgrass reveals a reversed north-south spatial pattern (Fig. 9b). The highest opportunity costs (>$988 ha^{-1}) cluster across most of Nebraska, southern South Dakota, and northern Kansas. In these counties, the baseline profitability of existing irrigated systems remains high, while switchgrass yields under dryland conditions are relatively low. As a result, switchgrass is economically unfavorable unless subsidized, integrated within multifunctional land-use contexts, or valued for its ecosystem services benefits. Conversely, eastern New Mexico and Oklahoma and the southern half of the Texas High Plains exhibit lower opportunity costs, frequently below $247 ha^{-1}. With several counties in these regions exhibiting crossover points where switchgrass becomes more cost-effective than dryland sorghum

a) **c)**



188 **Fig. 9. Spatial variation in opportunity cists for non-irrigated bioenergy crops across the**

189 **U.S. High Plains Aquifer region. a) The foregone profit relative to baseline irrigated corn,**

190 **representing the minimum incentive required to sorghum adoption under dryland**

191 **conditions. b) Analogous estimated for perennial switchgrass productions.**

192

4. Discussion

This study integrates hydrological modeling and economic optimization to explore sustainable cropping decisions under increasing groundwater constraints. By jointly examining water resource availability, crop productivity, and economic viability, we optimize agricultural systems that balance profitability and conservation. Our analysis highlights the complex interplay between aquifer depletion, irrigation economics, and bioenergy crop adoption, providing an understanding of how regional differences shape optimal land-use transitions.

The spatiotemporal transitions we observe emerge from the interaction of hydrogeological decline, pumping cost, and capital requirements for irrigation infrastructure as represented in the MILP framework. As aquifer transmissivity declines and total pumping head increases, water availability increasingly limits irrigation of the water-intensive crops such as corn (Steward et al., 2013, 2009; Steward and Allen, 2016). When the expected net returns fall short of covering the pivot investment cost, irrigation production exits discreetly in favor of dryland production. This dynamic of localized depletion dynamic is most seen in the southern and central High Plains, where aquifer decline and economic factors converge to accelerate the transition. Our 30-year optimization indicates that 0.68 million hectares (23%) of today's irrigated corn footprint across the High Plains will relinquish center-pivot irrigation, chiefly in the Texas Panhandle and western Kansas, where well capacities fall below the 18.9 L s^{-1} reinvestment threshold. By Year 30, Nebraska still supports irrigation on 78% of its initial groundwater volumes, while Texas retains only 41%--underscoring a strong north-south gradient in hydro-economic resilience. The model therefore reinforces the reframing of depletion not as a uniform decline but as a wave of localization (Scanlon et al., 2012), with vulnerability peaking where transmissivity is low and energy costs increases (Korus and Hensen, 2020).

The mixed-integer framework embeds a binary *go/no-go* variable 15-year pivot replacement. Once marginal revenues drop below $75,000 capital constraint, regions cascade into dryland pathways irrespective of residual saturated thickness. Aggregated discounted profits remain sizeable (US $12.3 billion over three decades), but 70% accrue to groundwater-rich Nebraska and northern Colorado, revealing how fixed-costs lumpiness amplifies geographic inequality in farm income. Policies that reduce the fixed cost of irrigation equipment, for example, through cost share programs, low-interest financing, delay (otherwise increase the life of the system) the timing of large capital investment, and thereby smooth regional transition (Foster et al., 2017; Pfeiffer and Lin, 2012). In the MILP framework, such policies effectively shift the binary investment constraint by lowering or delaying the fixed cost, thereby increasing the set of zones where irrigation remains economically viable beyond the 15-year replacement cycle.

4.1.1 Persistent Decline in Irrigated Corn

We project that the transition from irrigated corn to dryland production systems will continue as a primary adaptive response to declining aquifer conditions across the High Plains. Region-wide, the share of irrigated area supported by 31.5 L s^{-1} wells falls from 89.0% (year 1) to 75.3% (year 16) and 65.8% (year 30), while dryland increases from 5.5% to 23.1%. The non-uniform geography (Nebraska sustaining irrigation far longer than Texas/wester Kansas) matches documented north-south contrasts in availability of recharge and localized depletion (Deines et al., 2020; Haacker et al., 2016; McGuire and Strauch, 2024; Mrad et al., 2020). These transitions reflect strategic adjustments not only to physical limitations but also to diminishing economic returns on irrigation infrastructure investments (Pfeiffer and Lin, 2012). While groundwater depletion drives these patterns, they are also shaped by the relative yield potential of crops under non-irrigated conditions (Irmak S., 2015) and the financial viability of reinvesting in pivot systems. States with greater hydrogeological resilience such as Nebraska are to sustain irrigated corn over multiple investment cycles, whereas areas in Texas and Kansas exhibit earlier and more widespread shifts to dryland corn, including sorghum and switchgrass. Our findings suggest that identifying where and when such transitions occur is essential for anticipating the geographic distribution of future irrigation phaseouts and regionally appropriate crop and water management strategies.

4.1.2 Irrigated Sorghum as an Intermediate Substitute

The unimodal trajectory of irrigated sorghum marked by rapid expansion during the first investment period followed by retreat illustrates its role as an intermediate substitute under groundwater constraints. Irrigated sorghum remains competitive at intermediate wells (18.9-25.2 L s^{-1}), where water extracting energy cost reduces corn profitability. As well capacities decline further, however, irrigated sorghum no longer passes the reinvestment threshold and is replaced by dryland systems or switchgrass. This substitution pathway underscores the transitional role of sorghum and align with hydro-economic analyses of crop choice and irrigation behavior under declining aquifer dynamic head (Young et al., 2021).

4.1.3 Rapid Growth of Non-irrigated Systems and role of switchgrass

The expansion of rainfed production is driven by (i) negative present value for new pivots at the replacement node once the pumping lift requirements and available water are accounted for; (ii) the low switching cost of dryland corn, and (iii) soil-climate in subregions (e.g., Nebraska and Central Kansas) where precipitation and soil storage mitigate yield penalties. Empirical studies in the High Plains document strong corn yield response to irrigation deficits and the conditions under which dryland performance remains competitive – precisely the case in which our model shifts area at reinvestment period and stabilizes (Payero et al., 2006).

Within this transition, dryland sorghum plays central role in counties where rainfall reliability, soils with adequate plant-available water and temperature regimes collectively support stable grain production under deficit conditions (Colaizzi et al., 2004; Klocke et al., 2009). Sorghum's lower seasonal evapotranspiration, deeper rooting, and tolerance to intra-seasonal water stress reduce yield volatility relative to dryland corn under similar precipitation conditions (Staggenborg et al., 2008). Economically, this translates into water efficient productivity and lower risk when seasonal precipitation is uncertain (Dhuyvetter et al., 1996; Pfeiffer and Lin, 2014). In our results, Kansas is the leading example, where non-irrigated sorghum expands by 308% by year 30, displacing irrigated corn first at the reinvestment node and then persisting as a low-capital and water-resistant system.

Perennial bioenergy crop expands selectively where opportunity cost are low and irrigation is already retired. Switchgrass grows 35% region-wide, with particularly large proportional gains where irrigation exits early. The steady adoption of switchgrass signals an emerging opportunity for perennial bioenergy systems withing broader agroecological transitions. These systems may offer co-benefits in terms of soil conservation, carbon sequestration, and land resilience, while also contributing to diversified income in areas facing long-term groundwater exhaustion. For switchgrass, opportunity costs of producing the crop must exceed the net returns of dryland sorghum and dryland corn, as well as more favorable as a dryland option over irrigated alternative. Across the entire modeled region, we find limited evidence of profitable transitions from irrigated corn to irrigated sorghum, this reflects the absence of strong yield advantages under diminishing water availability and high capital intensity with irrigation system investment. Opportunity cost mapping shows that in the southern High Plains especially eastern New Mexico and the southern Texas Panhandle switchgrass out-competes dryland sorghum when opportunity costs fall below \$247 ha^{-1}. Central Nebraska, by contrast, presents the converse pattern, favoring sorghum due to dryland yields. Across the entire High Plains regions, 31% of the land exiting irrigation transitions to bioenergy crops, offering a perennial biomass supply with no new water withdrawals. This spatial bifurcation defines a “transition corridor” where relatively small policy adjustments in carbon pricing or biomass contracts incentives could unlock large-scale perennial adoption (Clifton-Brown et al., 2023).

The spatial inversion may be due to switchgrass’s perennial growth cycle and deep root systems, which confer yield stability under arid conditions and minimal input costs once established. The economics of adoption may be further improved in areas eligible for conservation cost-share programs or bioenergy procurement contracts. Notably, central Colorado and portions of eastern Wyoming show moderate opportunity costs (\$247 to 618 ha^{-1}), making switchgrass marginally viable depending on local cost structure and market access. Comparing the two maps reveals a striking spatial divergence in relative feasibility. Central Nebraska and northeastern Colorado show low opportunity costs for dryland sorghum but high costs for switchgrass, suggesting a clear preference for annual dryland cropping systems. In contrast, southern Texas Panhandle and easter New Mexico show the inverse, favoring switchgrass over sorghum due to low yields and better perennial biomass performance. This spatial contrast points to a “transition corridor” through central Kansas and easter Colorado, where opportunity costs for both crops are moderate (\$247 to 618 ha^{-1}). In these mixed-feasibility zones, crop producers may evaluate crop choice based on rotational preferences, risk aversion and available subsidies. These regions are likely to be most responsive to incremental changes in market signals and represent priority areas. The results also identify “resistant zones” where high opportunity cost for both crops (>\$988 ha^{-1}) prevail. These include the core irrigated regions of central Nebraska and some areas the Texas High Plains where neither dryland sorghum nor switchgrass is currently economically viable. These areas face the highest risk of abrupt productivity loss if irrigation becomes unsustainable.

4.1.4 Synthesis

By dynamically downgrading wells from31.5 to 6.3 L s^{-1}, the optimization preserves more than one-third of initial groundwater that would otherwise be exhausted under static management. Yet rising pumping lift costs still reduce net returns in the southern High Plains, showing that demand-side efficiency must be paired with low energy to stabilize the farm margins (Steward et al., 2009). The model’s coupling of hydraulic strata with depth-specific pumping coefficients provides a foundation for future energy-water-trade-off analyses under climate and policy scenarios.

The noticeable heterogeneity in both hydrogeology and opportunity costs demonstrates that a uniform policy instrument, whether applied through aquifer-wide management districts or broader regional authorities would distribute costs and benefits unevenly. Our results suggest that groundwater governance in the High Plains will similarly require place-based, calibrated to local hydrogeologic conditions and opportunity costs, rather than a single basin wide management approach. Instead, our findings support a tiered approach to water and crop management, (i) maintain high-value irrigation in zones with adequate recharge and transmissivity, (ii) accelerate pivot retirement and dryland diversification where aquifer exhaustion is imminent, and (iii) target incentives for perennials in the transition corridor where they are most likely to succeed. Because adaptation is already underway in response to economic signals, timely, place-based policies can amplify local decision-making and steer the system toward jointly optimized economic and hydrological outcomes. transmissivity, (ii) accelerate pivot retirement and dryland diversification where aquifer exhaustion is imminent, and (iii) target incentives for perennials in the transition corridor where they are most likely to succeed. Because adaptation is already underway in response to economic signals, timely, place-based policies can amplify local decision-making and steer the system toward jointly optimized economic and hydrological outcomes.

Together, these insights affirm that integrated economic-hydrologic optimization is essential for characterizing regionally nuanced pathways that secure both farm benefits and aquifer longevity.

4.1.5 Limitations & uncertainty

Our findings should be interpreted considering several methodological and data-related limitations that collectively bound the confidence we can place in the absolute magnitudes of projected land-use change, biomass supply and economic returns.

The optimization framework treats each county as a single-cell aquifer with homogeneous hydraulic properties and no lateral fluxes. This assumption was necessary to maintain tractability across 180 counties, but it masks fine-scale heterogeneity in saturated thickness, transmissivity, and irrigation drawdown that strongly influence well performance at the field scale. Consequently, the maps created may over or under-state trajectories where local transmissivity differs significantly from county means. Incorporating cell-to-cell leakage or fully coupled groundwater flow models (e.g., MODFLOW) would sharpen spatial contracts but was beyond the scope of this economic analysis. Aquifer attributes were driven from raster products (GLHYMPS permeability, USGS saturated thickness and LANID irrigation masks) with native resolution of 500 m that were scaled up to county means. Errors due to mixed pixels, noise, and extrapolation of well-data propagate directly into effective well-capacity classes that estimate our yield functions. A ±10% error in saturated thickness translates to an error in the drawdown cost coefficient, and this uncertainty is not reflected in the deterministic MILP.

All simulations hold annual recharge, growing season precipitation, and evapotranspiration demand at their recent climatological means. They therefore omit two sources of uncertainty that are likely to grow over the 30-year horizon, (i) intensifying summer aridity across the southern High Plains, and (ii) the coincident tendency for extreme rainfall events to increase recharge non-linearly. Either process could accelerate or dampen the decline in effective irrigation capacities shown in Fig. 4. Furthermore, relative yield curves for corn and sorghum were fitted to four experimental sites (western CO, western KS, SW NE, and TX High Plains) and then applied uniformly across the entire Ogallala region. While piece-wise linearization captures first-order biophysical responses, it ignores environmental interactions and soil textural effects. In regions with heavier soils or late maturing hybrids, the model may under predict yields at low pumping rates, in early maturity regions it may over predict.

The analysis assumes (i) a real discount rate of 7%, (ii) 2018-2023 average commodity prices and input costs were held constant in real terms, and (iii) a fixed $75,000 capital costs for a new center-pivot that is replaced exactly in year 16. This approach slightly inflates the initial investment cost and does not precisely reflect current infrastructure realities, but the influence of this assumption diminishes significantly over multiple pivot replacement cycles. Sensitivity tests by adjusting discount rate and future prices may not overturn the qualitative ranking of the regions, but they could shift the timing of the pivot investment. Furthermore, pumping energy requirements were calculated with depth specific kWh m^{-3} coefficients, but natural gas prices were held at the 2023 averages. It neither prices CO_2 emissions from pumping nor credits soil-carbon accumulation under switchgrass. Internalizing externality would tilt results towards lower-energy systems and perennial feedstock, respectively, but the magnitude is policy-contingent and therefore excluded.

We assume no new groundwater use regulations, no changes to the Renewable Fuel Standard or other energy incentives or programs like a Clean Fuel Program, and no dedicated biomass supply contracts. A stricter pumping limitation, a carbon fuel standard, or perennial-crop incentives could accelerate the transitions forecast; conversely, subsidized irrigation energy could delay them. Because such policies are inherently uncertain and jurisdiction-specific, they were left for scenario analysis in future work.

Peripheral counties with < 1000 km^2 overlying the aquifer were excluded to ensure analytical relevance. While these areas account for <4% of the current irrigated corn, they can act as hydrological buffers or recharge corridors, excluding them slightly inflating average depletion rates in bordering counties. The MILP yields single, "mostly-effective" solution for each county under the assumed parameters. We did not propose parameters of uncertainty through stochastic weather or price shocks. Future work should adopt stochastic dynamic programming or robust optimization to generate decision spaces that account for parameter and process uncertainty.

Finally, we caution against extrapolating the absolute magnitudes of land-use change beyond 30 years horizon. The pivot-replacement schedule, aquifer drawdown, and technological advances (e.g., subsurface drip, deficit-irrigation algorithms) will interact in ways that cannot be forecast linearly. The qualitative insight that groundwater scarcity will forecast spatial variation of high-capacity irrigation, also exact area should be revisited as new monitoring data and economic parameters becomes available. These caveats underline that our estimates are intentionally conservative and best viewed as *directional* rather than *predictive*. They serve to bound the problem, highlighting where improved data would most reduce uncertainty (e.g., high-resolution recharge rates, county-level pivot age), and provide a transparent platform for scenario testing under alternative weather, market, or policy futures.

5. Conclusions

Policy implications from this study are clear and actionable: policymakers and resources managers can prioritize initiatives that promote sustainable groundwater use, encourage diversified cropping systems, and support investments in irrigation efficiency improvements. Programs aimed at incentivizing the adoption of bioenergy crops and enhancing the economic resilience of agricultural communities can help accelerate transitions away from unsustainable cropping practices, while maintaining farm profitability and supporting rural livelihoods. Methodologically, the use of a MILP model coupled with remote sensing and GIS-based aquifer characterization – provided robust and nuanced insights into crop management strategies. Although our single-cell aquifer assumption and uniform pivot investment timing simplify complex hydrological realities, these methodological choices facilitate broader strategic comparisons and illustrate critical long-term trends clearly. Future research should incorporate spatially explicit data and staggered investment cycles to refine short and medium-term decisions.

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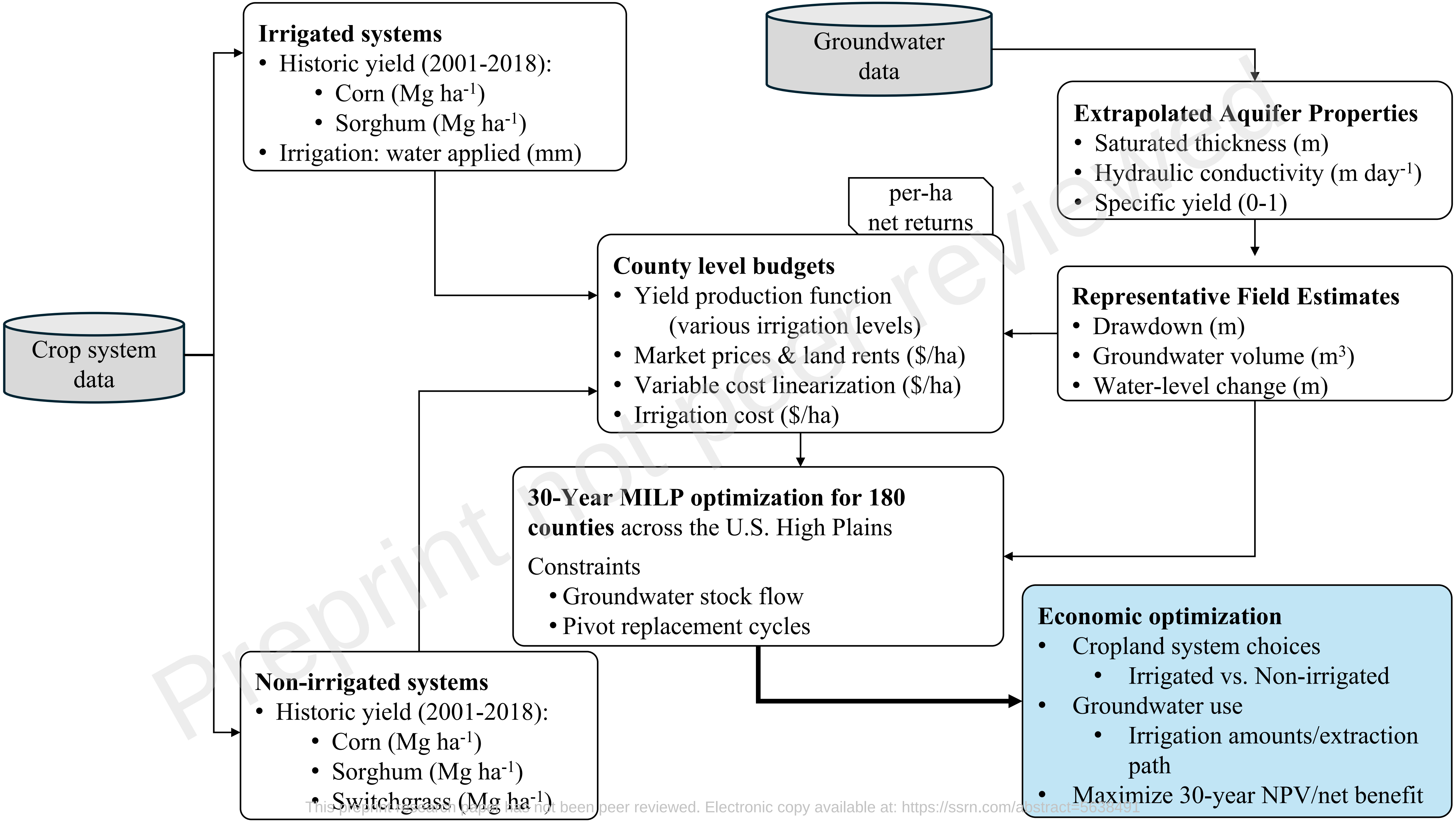
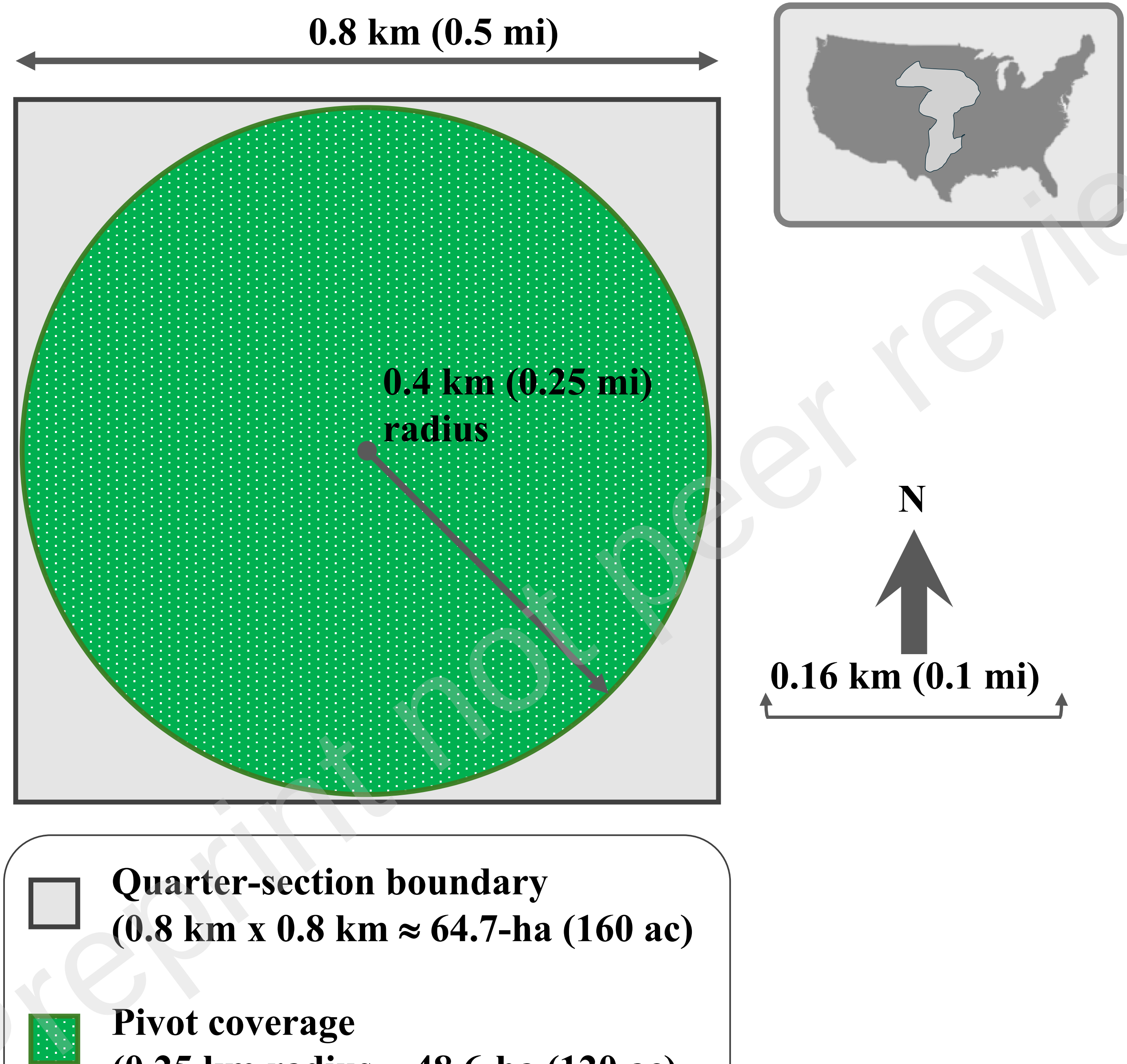
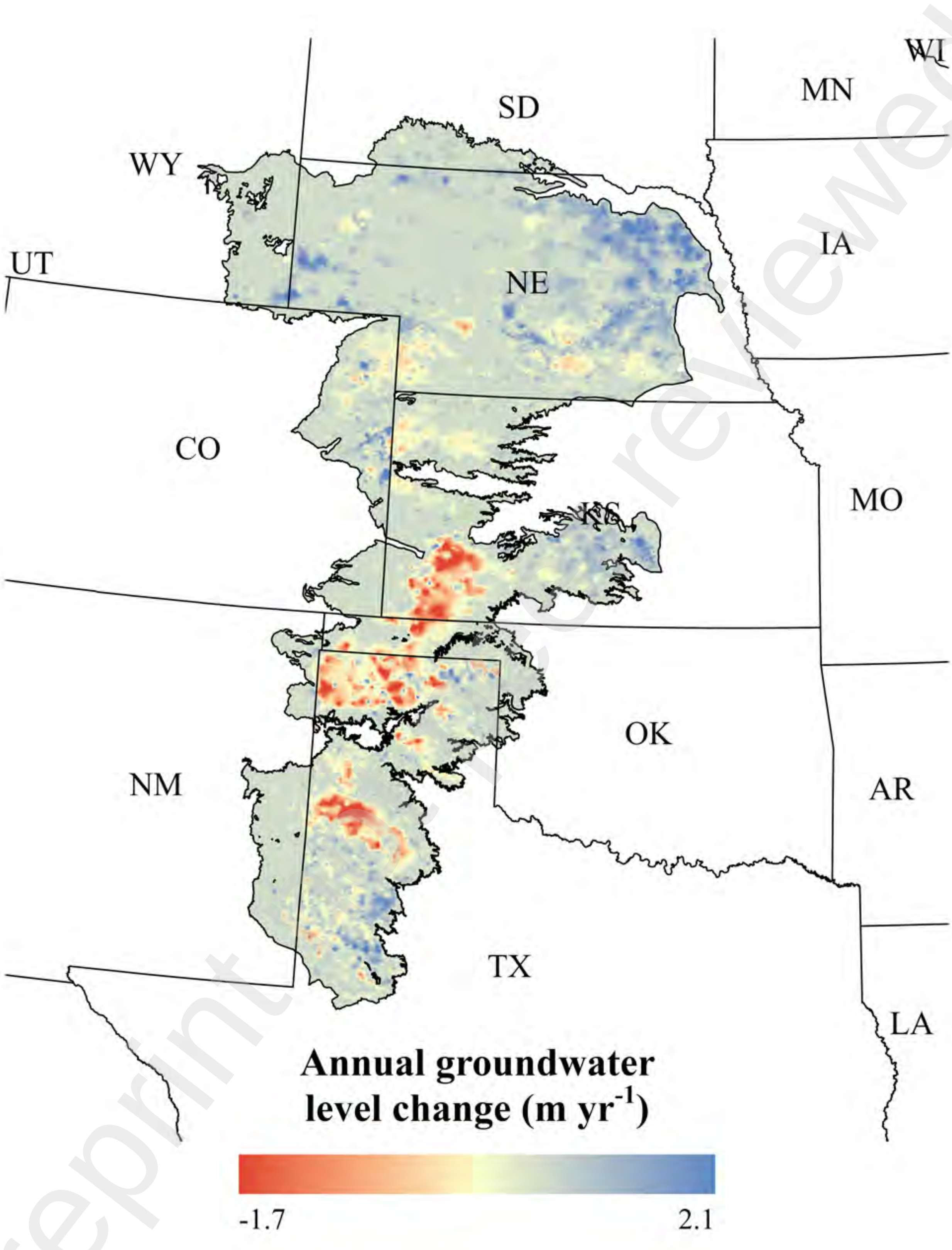

Crop system data
Irrigated systems
• Historic yield (2001-2018):
• Corn (Mg ha-1)
• Sorghum (Mg ha-1)
• Irrigation: water applied (mm)
Groundwater data
Extrapolated Aquifer Properties
• Saturated thickness (m)
• Hydraulic conductivity (m day-1)
• Specific yield (0-1)
per-ha net returns
County level budgets
• Yield production function (various irrigation levels)
• Market prices & land rents ($/ha)
• Variable cost linearization ($/ha)
• Irrigation cost ($/ha)
Representative Field Estimates
• Drawdown (m)
• Groundwater volume (m3)
• Water-level change (m)
30-Year MILP optimization for 180 counties across the U.S. High Plains
Constraints
• Groundwater stock flow
• Pivot replacement cycles
Non-irrigated systems
• Historic yield (2001-2018):
• Corn (Mg ha-1)
• Sorghum (Mg ha-1)
• Switchgrass (Mg ha-1)
Economic optimization
• Cropland system choices
• Irrigated vs. Non-irrigated
• Groundwater use
• Irrigation amounts/extraction path
• Maximize 30-year NPV/net benefit



0.8 km (0.5 mi)
0.4 km (0.25 mi)
radius
N
0.16 km (0.1 mi)
Quarter-section boundary
(0.8 km x 0.8 km ≈ 64.7-ha (160 ac)
Pivot coverage
(0.25 km radius ≈ 48.6-ha (120 ac)



WI
MN
SD
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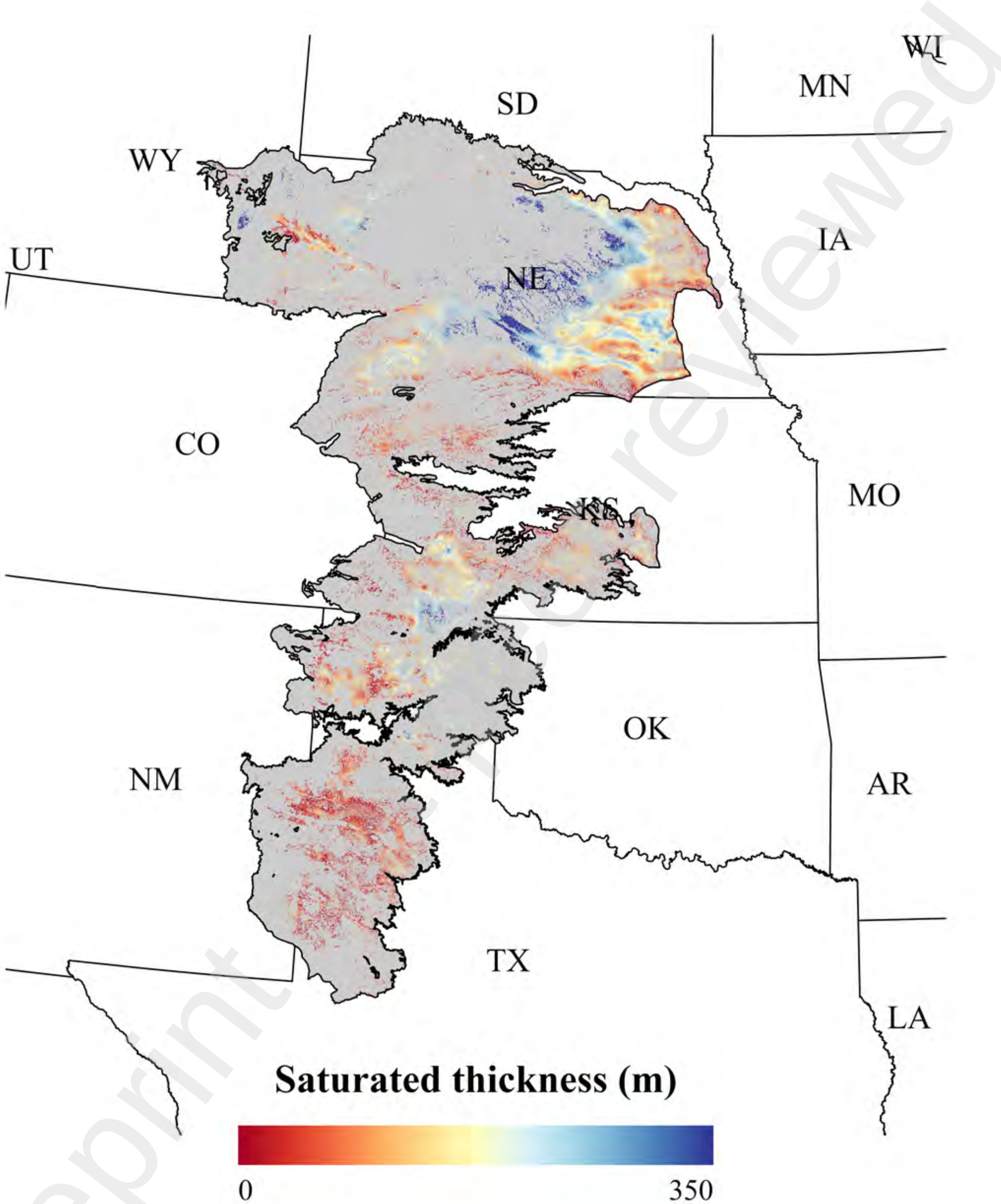
LA
Annual groundwater level change (m yr-1)
-1.7
2.1


WI
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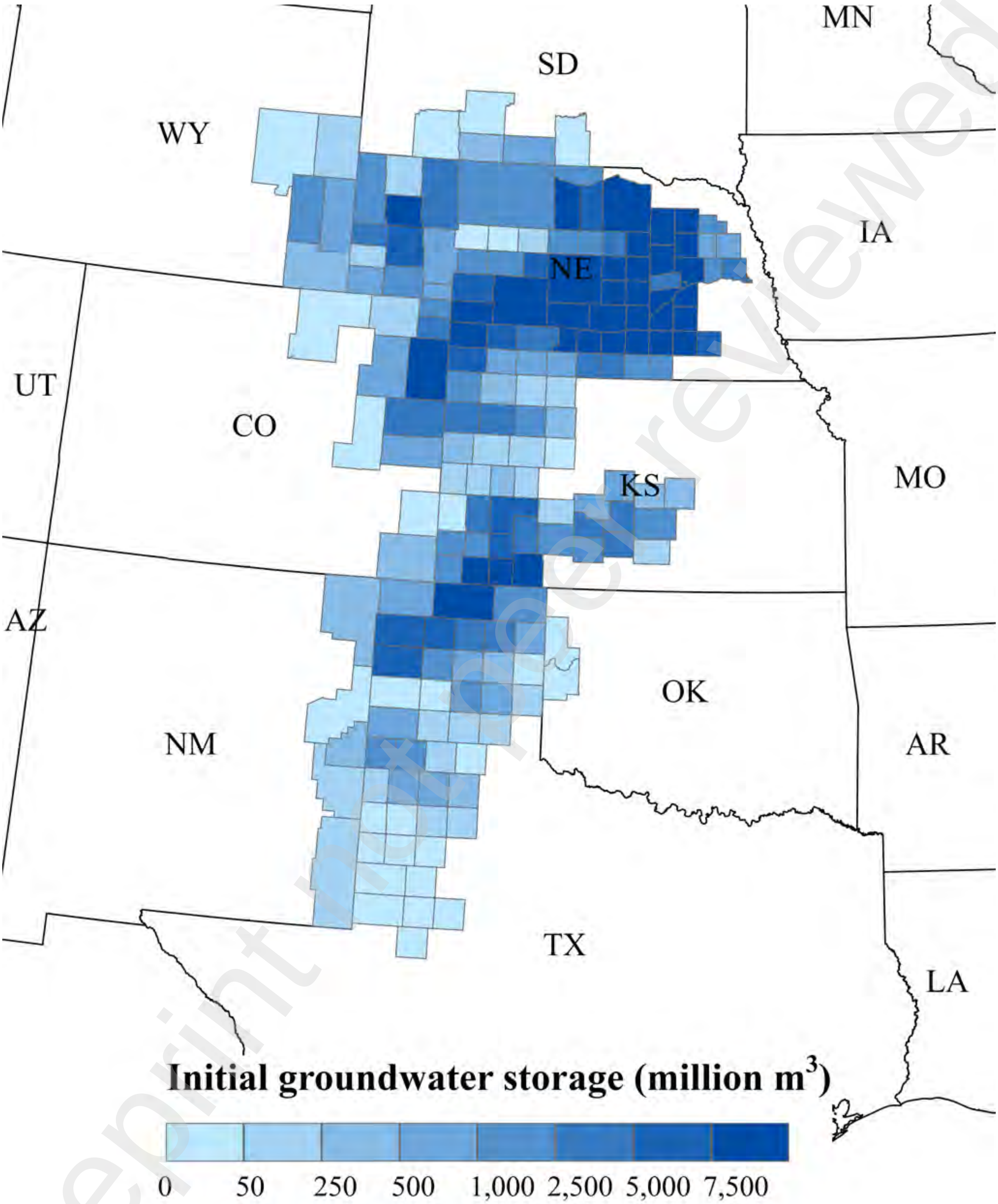
Saturated thickness (m)
0
350


MN
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AZ
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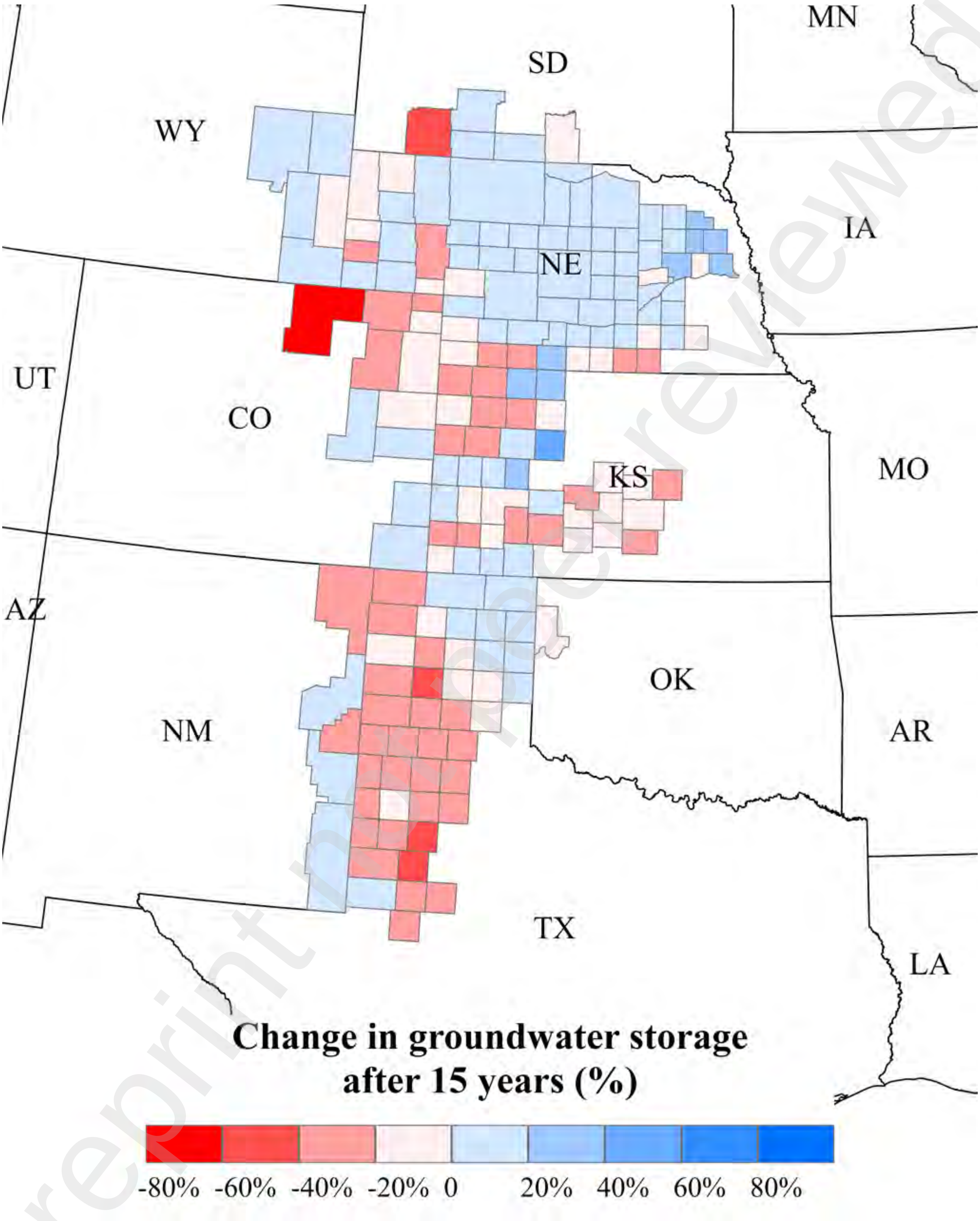
AR
TX
LA
Initial groundwater storage (million m³)
0
50
250
500
1,000
2,500
5,000
7,500


MN
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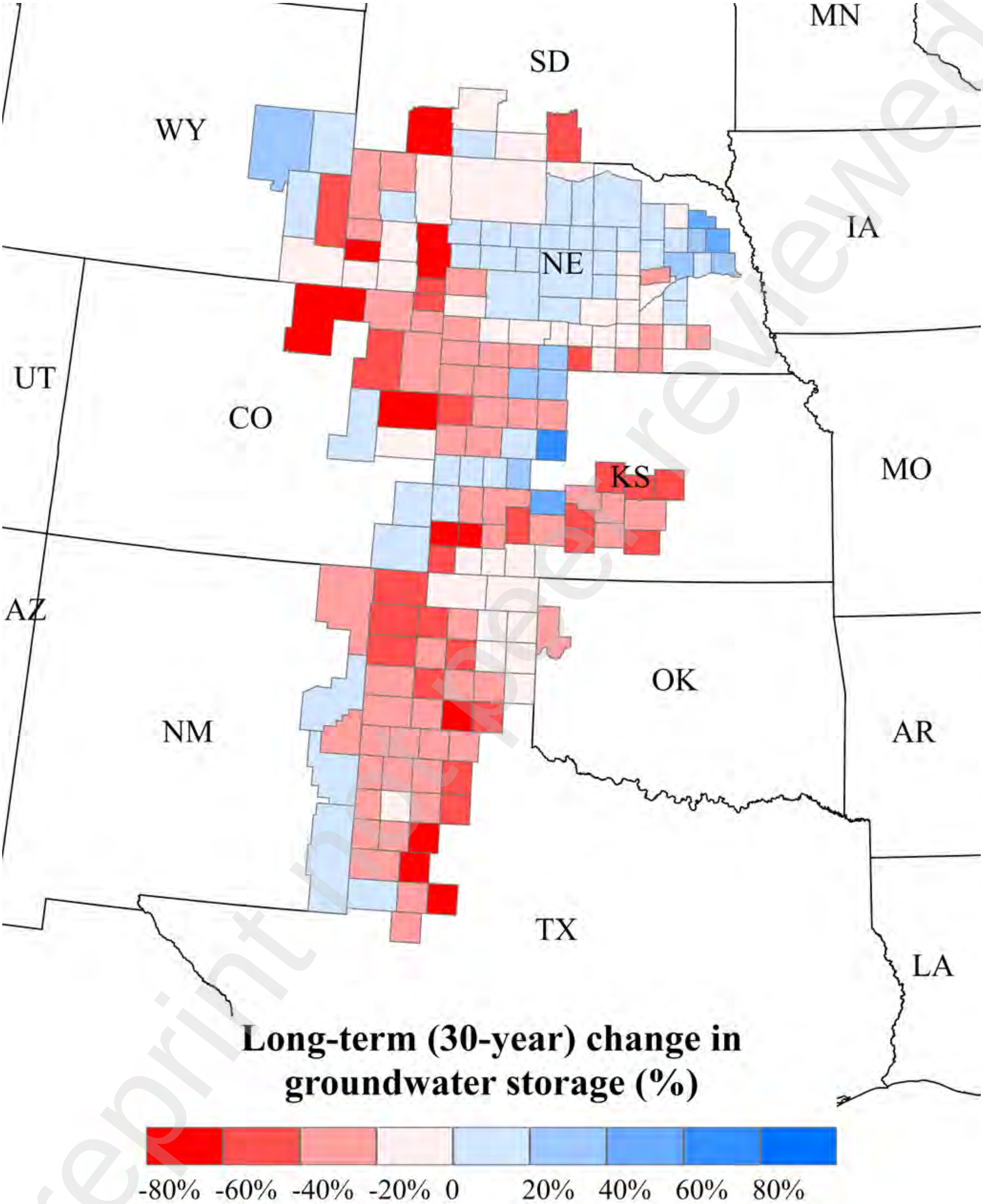
LA
Change in groundwater storage after 15 years (%)
-80% -60% -40% -20% 0 20% 40% 60% 80%


MN
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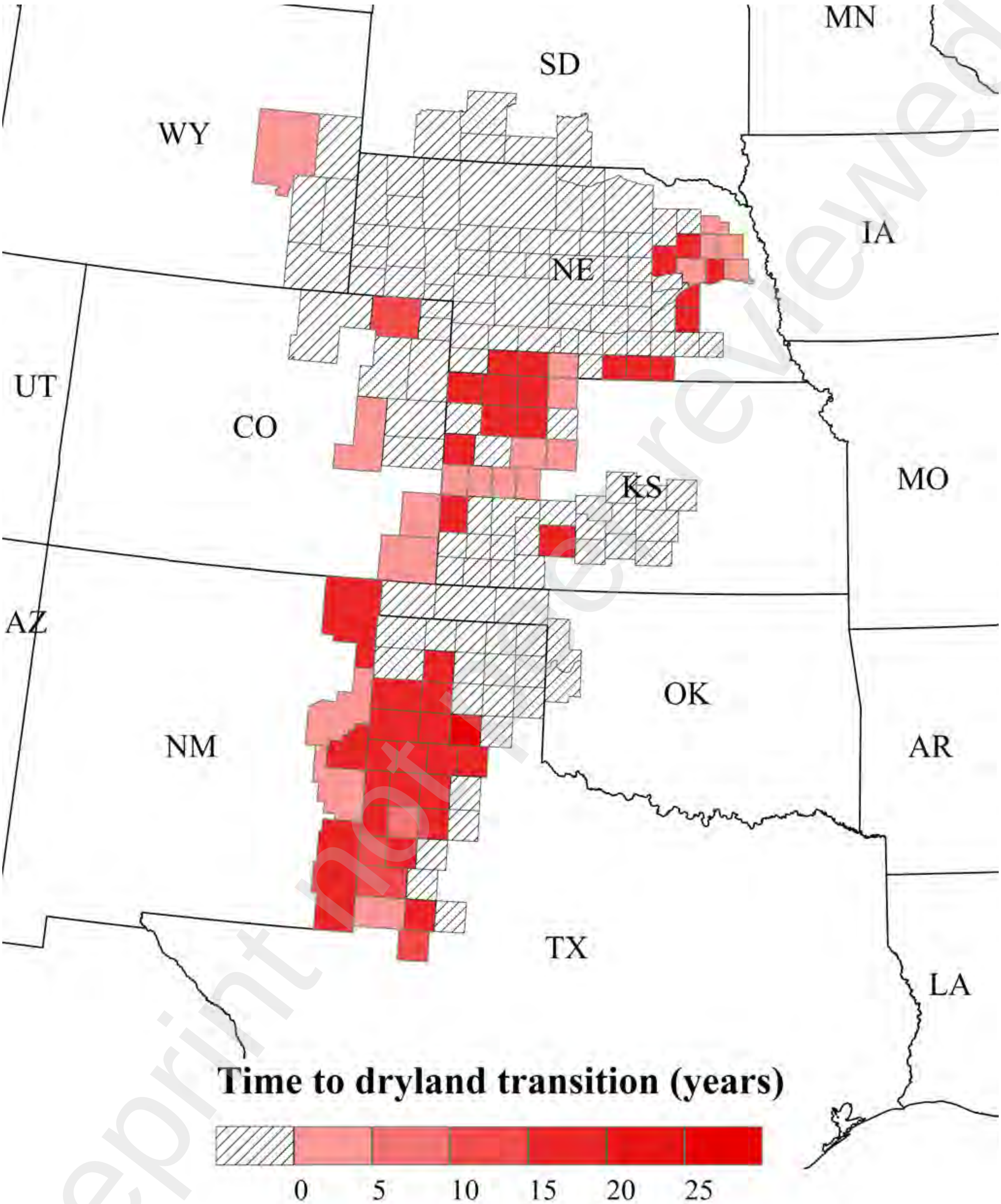
TX
LA
Long-term (30-year) change in groundwater storage (%)
-80% -60% -40% -20% 0 20% 40% 60% 80%


MN
SD
WY
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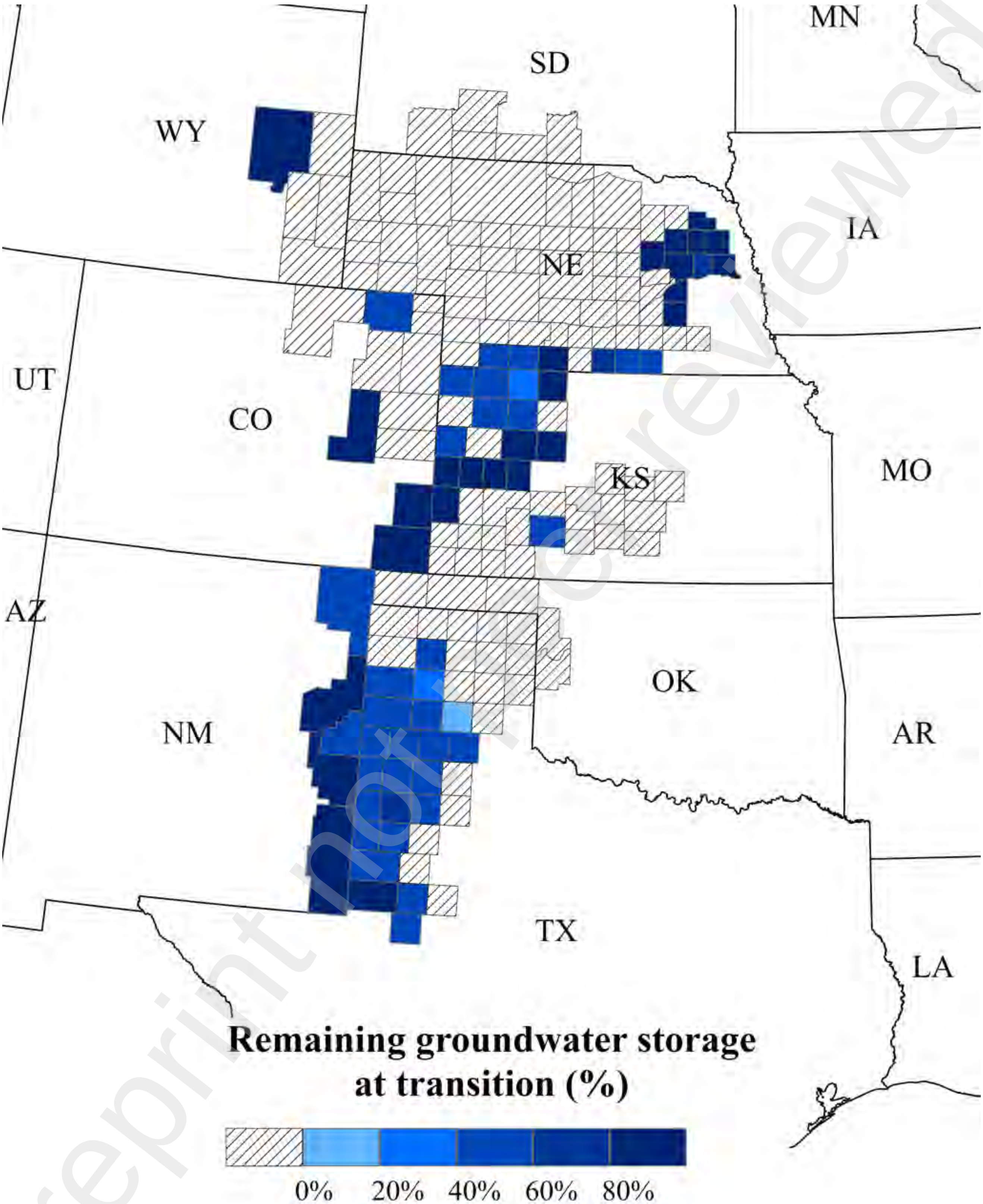
AR
TX
LA
Time to dryland transition (years)
0
5
10
15
20
25



MN
SD
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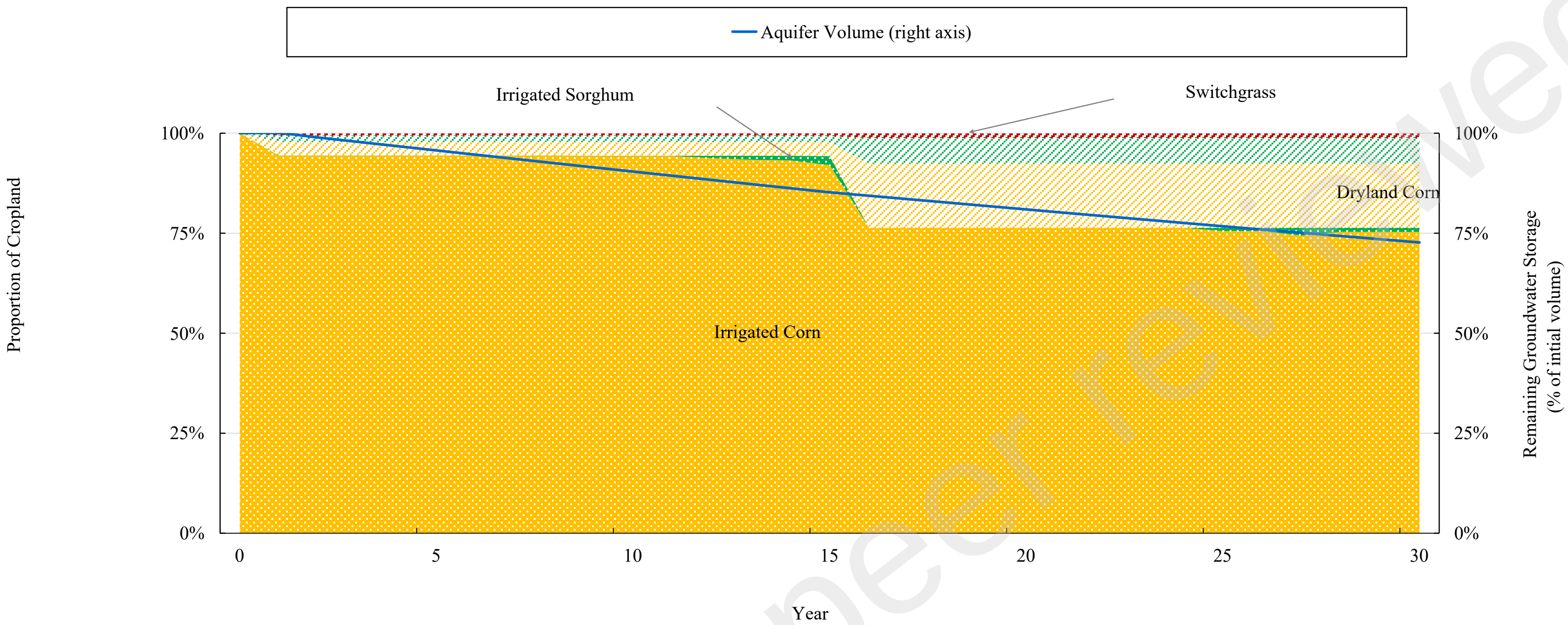
LA
Remaining groundwater storage at transition (%)
0%
20%
40%
60%
80%

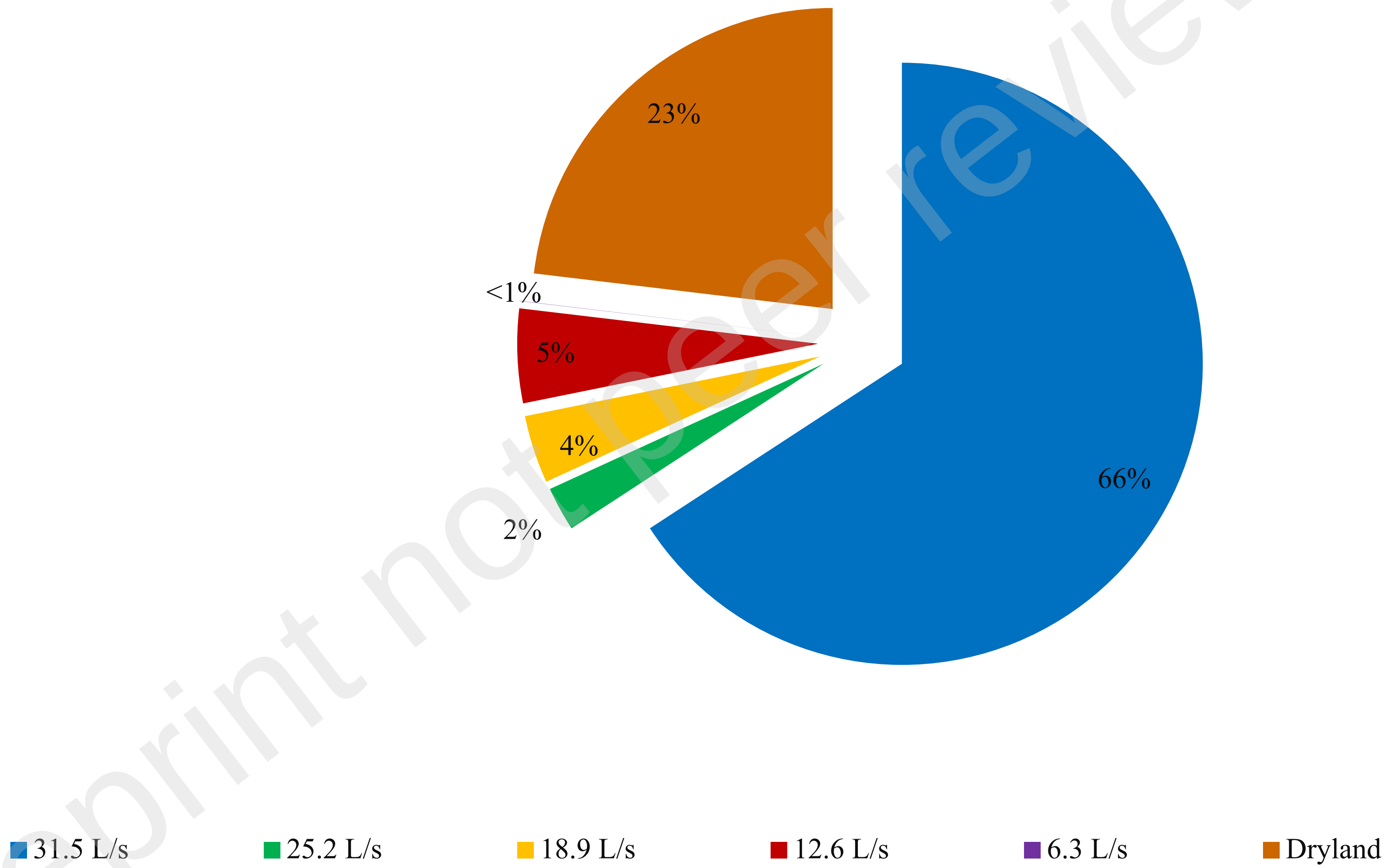


Aquifer Volume (right axis)
Irrigated Sorghum
Switchgrass
100%
75%
50%
25%
0%
Proportion of Cropland
Dryland Corn
Irrigated Corn
Remaining Groundwater Storage
(% of intial volume)
0
5
10
15
20
25
30
Year

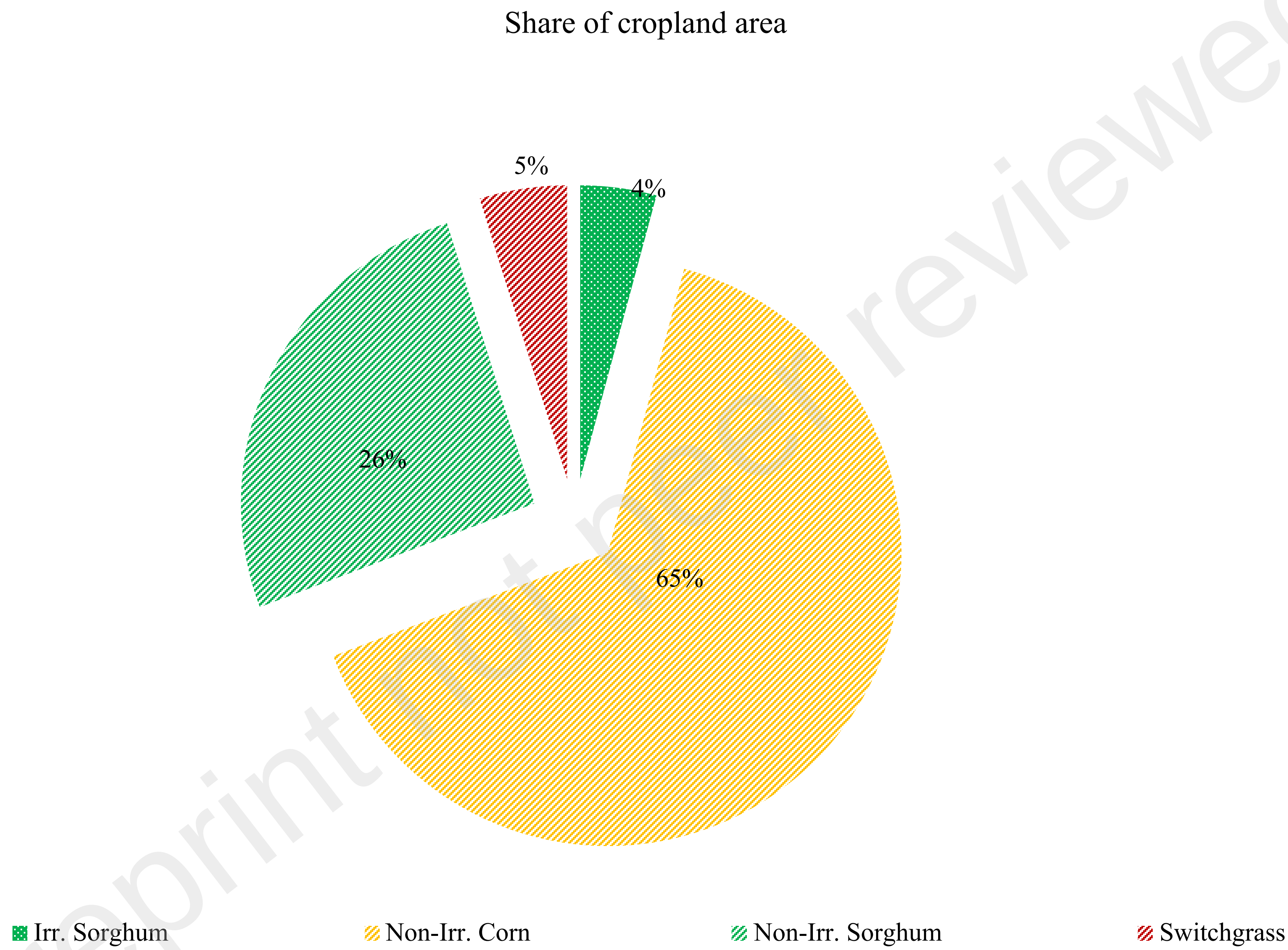
Year	Irrigated Cor	Irrigated Sorghum	Non-Irrigated Corn	Non-Irrigated Sorghum
0	6917141	0	0	0
1	6917141	4,863	251,082	112,974
2	6,917,141	4,863	251,082	112,974
3	6,917,141	4,863	251,082	112,974
4	6,917,141	4,863	251,082	112,974
5	6,917,141	4,863	251,082	112,974
6	6917141	4,863	251,082	112,974
7	6917141	4,863	251,082	112,974
8	6917132	4,872	251,082	112,974
9	6914260	4,872	253,953	112,974
10	6914260	4,872	253,953	112,974
11	6913752	4,872	254,462	112,974
12	6875010	43,614	254,462	112,974
13	6844691	73,123	255,272	112,974
14	6833782	84,031	255,272	112,974
15	6747066	165,859	255,281	112,974
16	5600428	9	1,175,090	468,674
17	5600428	9	1,175,090	468,674
18	5600428	9	1,175,090	468,674
19	5600428	9	1,175,090	468,674
20	5600428	9	1,175,090	468,674
21	5600428	9	1,175,090	468,674
22	5600428	9	1,175,090	468,674
23	5600428	9	1,175,090	468,674
24	5600428	9	1,175,090	468,674
25	5537998	62,439	1,175,090	468,674
26	5537998	62,439	1,175,090	468,674
27	5453042	147,395	1,175,090	468,674
28	5524769	75,668	1,175,090	468,674
29	5523350	75,668	1,176,509	468,674
30	5523350	75,668	1,176,509	468,674

Switchgrass	Aquifer Volume (right axis)
0	100.00%
45,284	100.00%
45,284	98.92%
45,284	97.84%
45,284	96.77%
45,284	95.70%
45,284	94.63%
45,284	93.57%
45,284	92.51%
45,284	91.46%
45,284	90.41%
45,284	89.36%
45,284	88.32%
45,284	87.28%
45,284	86.25%
50,164	85.23%
87,142	84.37%
87,142	83.51%
87,142	82.66%
87,142	81.80%
87,142	80.95%
87,142	80.09%
87,142	79.25%
87,142	78.41%
87,142	77.57%
87,142	76.74%
87,142	75.91%
87,142	75.10%
87,142	74.30%
87,142	73.49%
87,142	72.69%

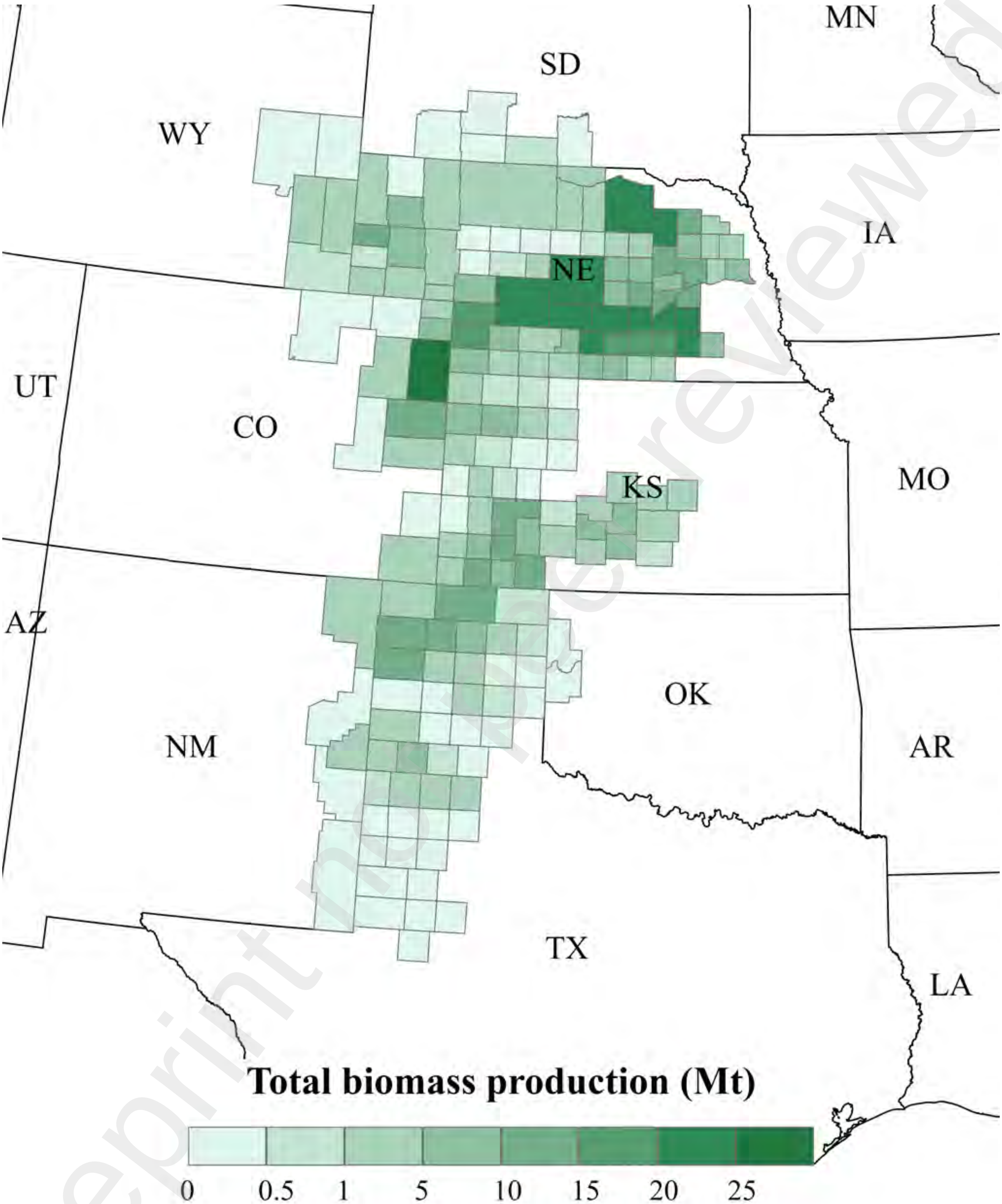
Irrigation capacity and Dryland breakdown

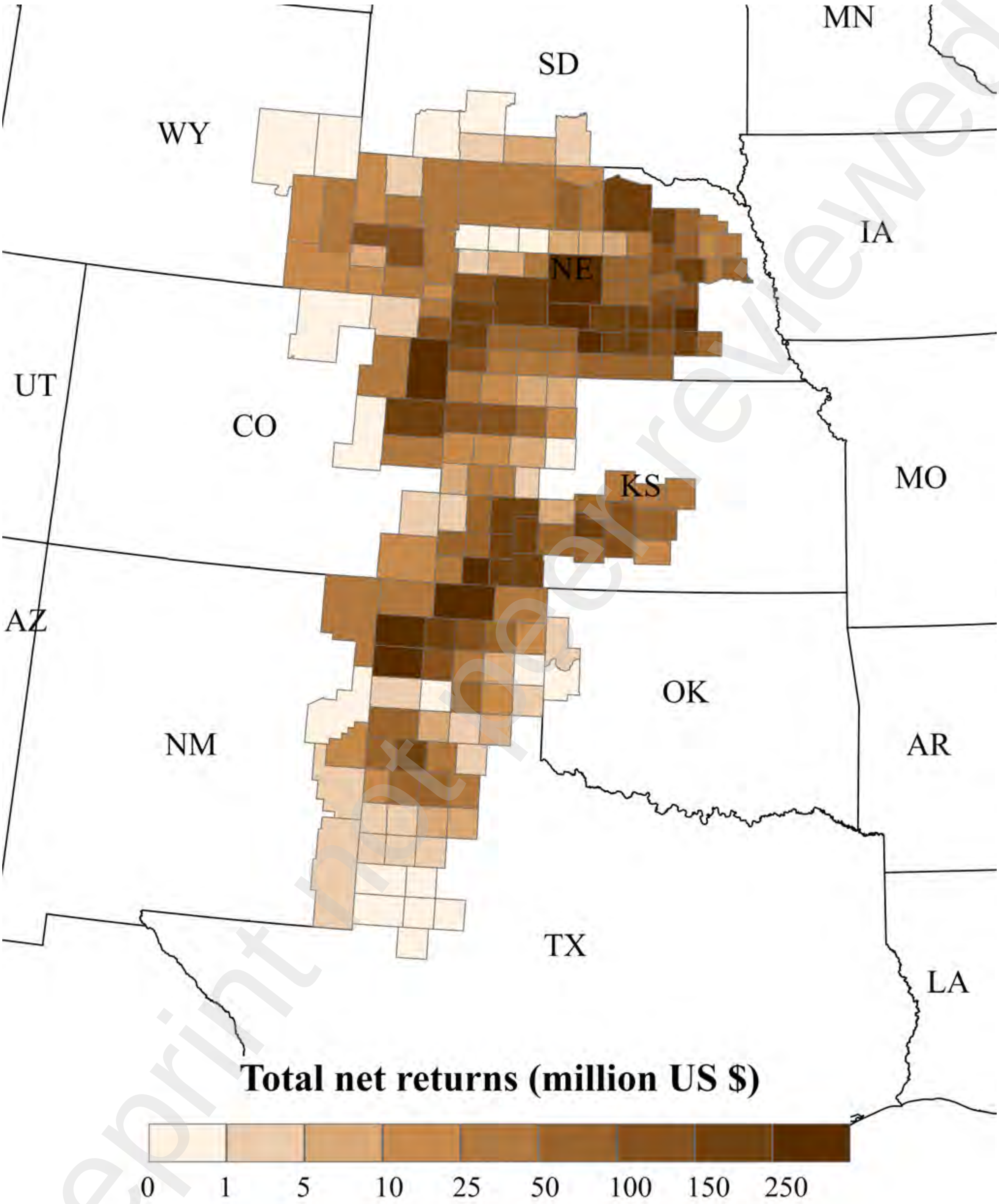


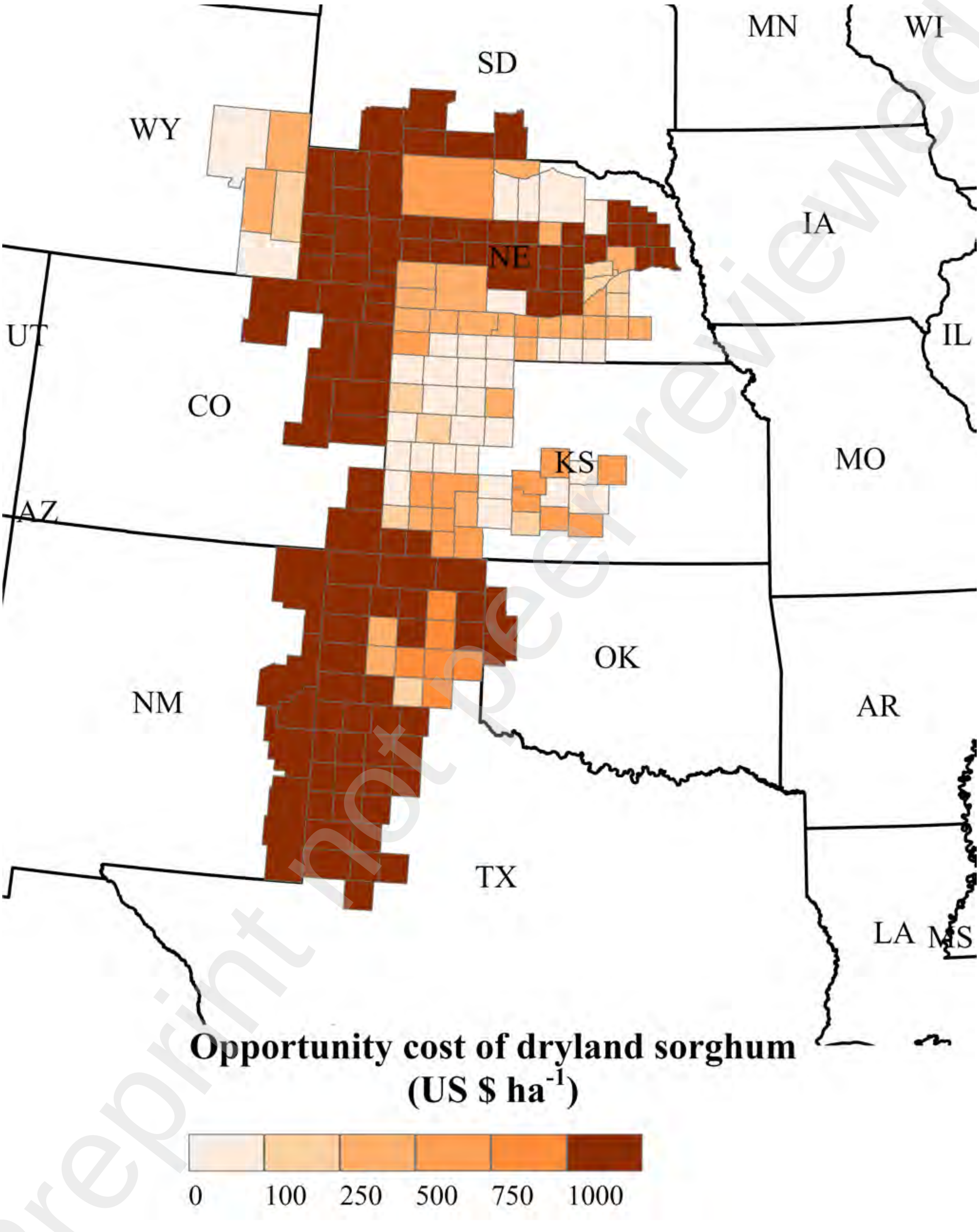
	Area
31.5 L/s	1,952,259
25.2 L/s	70,419
18.9 L/s	108,278
12.6 L/s	149,979
6.3 L/s	374
Dryland	685,645

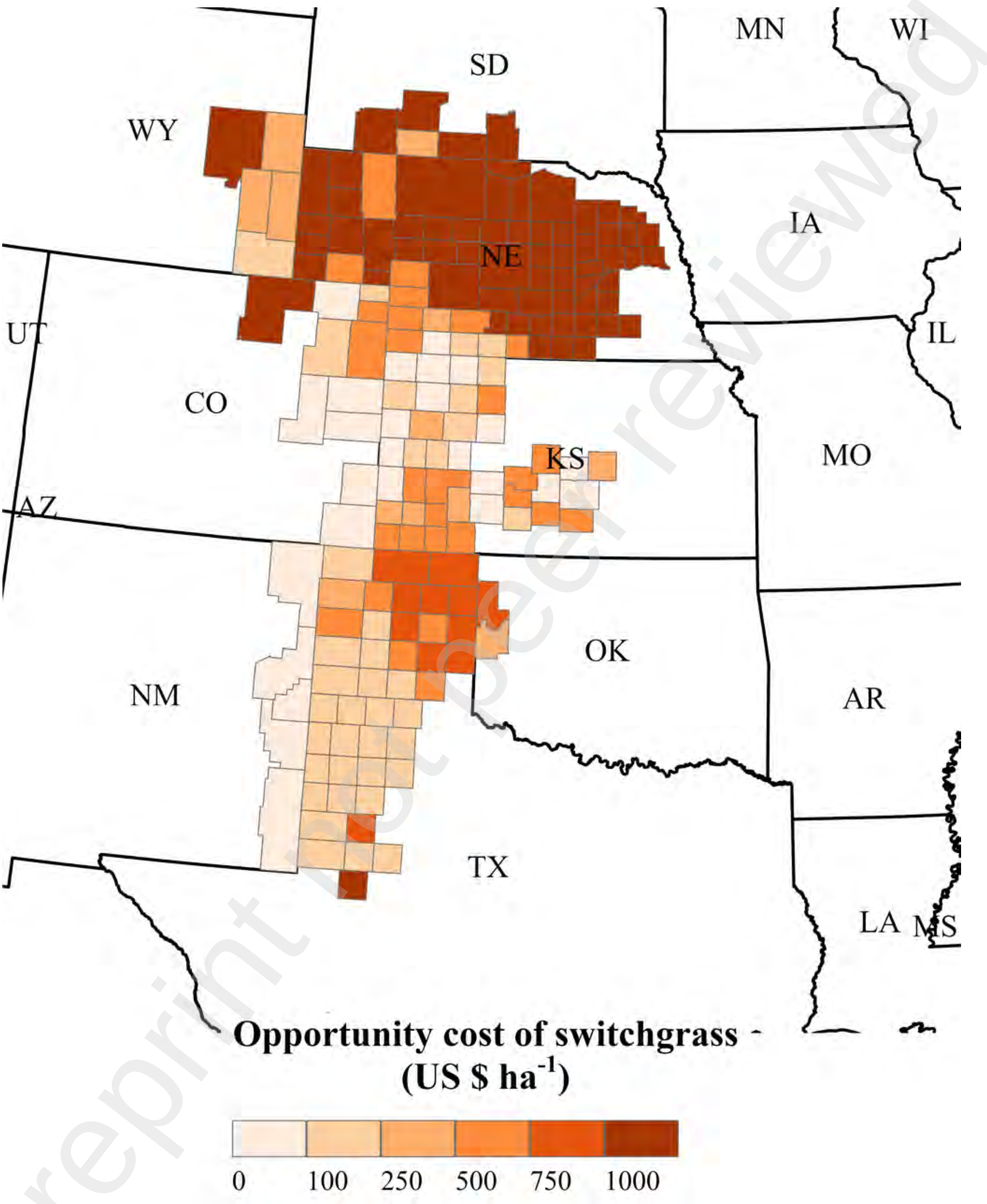

Share of cropland area
5%
4%
26%
65%
Irr. Sorghum
Non-Irr. Corn
Non-Irr. Sorghum
Switchgrass

	Area
Irr. Sorghum	0.08
Non-Irr. Corn	1.18
Non-Irr. Sorghum	0.47
Switchgrass	0.09


MN
SD
WY
IA
NE
UT
CO
MO
KS
AZ
OK
NM
AR
TX
LA
Total biomass production (Mt)
0
0.5
1
5
10
15
20
25


MN
SD
WY
IA
NE
UT
CO
MO
KS
AZ
OK
NM
AR
TX
LA
Total net returns (million US $)
0
1
5
10
25
50
100
150
250


MN
WI
SD
WY
IA
NE
UT
IL
CO
MO
KS
AZ
OK
NM
AR
TX
LA
MS
Opportunity cost of dryland sorghum
(US $ ha^-1)
0
100
250
500
750
1000


MN
WI
SD
WY
IA
NE
UT
IL
CO
MO
KS
AZ
OK
NM
AR
TX
LA
MS
Opportunity cost of switchgrass
(US $ ha-1)
0
100
250
500
750
1000