

RESEARCH ARTICLE

Perennial biomass crops on marginal land improve both regional climate and agricultural productivity

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Abstract

Perennial grasses can reduce soil erosion, restore carbon stocks, and provide feedstocks for biofuels and bioproducts. Here, we show an additional benefit, amelioration of regional climate warming, and drying. Growing *Miscanthus × giganteus*, an example of perennial biomass crops, on US marginal land cools the Midwest Heartland summer by up to 1°C as predicted by a new coupled climate-crop modeling system. This cooling is mainly caused by the increased duration and size of the *Miscanthus × giganteus* leaf canopy when compared with the existing vegetation on marginal land, resulting in larger solar reflection, more evapotranspiration, and decreased sensible heat transfer. Summer rainfall is increased through mesoscale circulation responses by 23–29 mm (14%–15%) and water vapor pressure deficit reduced by 5%–13%, lowering potential transpiration for all Midwest crops. Similar but weaker effects are simulated in the Southern Heartland. This positive feedback through the climate–crop interaction and teleconnection leads to 4%–8% more biomass production and potentially 12% higher corn and soybean yields, with greater yield stability. Growing perennials on marginal land could be a feasible solution to climate change mitigation and adaptation by strengthening food security and providing sustainable alternatives to fossil-based products.

KEYWORDS

bioenergy crops, biomass crop, coupled climate–crop system, land use change, land–atmosphere feedback, marginal land, sustainable agriculture

1 | INTRODUCTION

Perennial biomass crops can potentially be 4–15 times more effective than forest and grassland conservation in reducing CO₂ emissions and mitigating climate change even after taking account of carbon emissions from land-use changes and opportunity costs (Field et al., 2020). In the arable landscape of the US Corn Belt, which contains 90 million hectares (Mha) of soy–corn rotation, perennials can rebuild soil carbon and fertility to eroded soils (Hansen et al., 2004; Horton et al., 2021). This would help toward reversing the recently estimated loss of about one-third of the regions' A-horizon soil and, with it, 1.4 petagrams (Pg) of carbon (Thaler et al., 2021). Perennials can also reduce nitrogen losses to waterways when planted in strips along the contours of sloping land (Schulte et al., 2017). Furthermore, with the growing demand for renewable products (Jaiswal et al., 2019) and biofuels, a diversity of markets for biomass is providing a rising economic, as well as sustainability, incentive for farmers (Brandes, McNunn, et al., 2018; Brandes et al., 2018).

Perennial biomass crops may also help to improve the resilience of cropping systems in the face of climate change. Rising temperatures and water vapor pressure deficits (VPD) are projected in the Midwest and are predicted to significantly lower food and feed crop yields due to water stress and supra-optimal temperature inhibition of leaf photosynthesis (Challinor et al., 2014; Lobell et al., 2014; Ort & Long, 2014). Evapotranspiration (ET) from cropping systems strongly affects regional climate, decreasing both temperature and VPD (Sellers et al., 1996). However, these benefits are partially offset by the physiological impacts of rising atmospheric carbon dioxide concentration ([CO₂]) (Le et al., 2011), in particular decreased stomatal apertures. Perennial biomass crops grow leaves earlier than annual food and feed crops, maintain a larger leaf canopy through the growing season and continue for 2–3 months after food and feed crops have dried down. As a result, they have higher ET and albedo, producing both cooling and wetting effects on regional climate (Georgescu et al., 2011; Loarie et al., 2011a). Local cooling can lessen the adverse impact of rising temperatures on agriculture, including food and feed crops (Lobell & Asner, 2003; Porter, 2005).

Marginal land areas suitable for perennial biomass crops in the United States are estimated at 43–123 Mha, which can be utilized without competing directly with annual food and feed crop production (Cai et al., 2011), while providing a sustainable economic use of this land. Much of this land is abandoned or low yielding crop land, in which soil quality has often been degraded through erosion or is land that would be easily degraded if brought into annual crop use. Land use changes of these areas

could have multiscale impacts on the regional climate, water quantity and quality (Robertson et al., 2017; Vera et al., 2021). In addition, planting perennial strips within productive corn–soybean land can pay for itself by preventing soil erosion and soil carbon losses to maintain the productive quality of that land (Jin et al., 2019; Schulte et al., 2017). Changing existing vegetation to productive perennial grasses has been projected in previous studies to cause significant regional cooling of 0.5 and 0.6°C in the United States (Georgescu et al., 2011) and Brazil (Loarie et al., 2011a), respectively. It is important to note that this climate improvement by establishment of these productive grasses will feedback on the grasses themselves to improve their production as well as other crops in the region. Via teleconnections, this would also result in positive changes in climate in distant locations (DeAngelis et al., 2010; Levis et al., 2012; Sleeter et al., 2018; Zhu & Liang, 2013).

Previous modeling studies used existing climate data, but did not consider how the impact that the alteration of climate caused by the crop would feedback on its own growth and yield (Jaiswal et al., 2017; Larsen et al., 2016; Miguez et al., 2012; Wang et al., 2015). Including the two-way interaction between crop and climate is necessary for quantifying the impact of planting perennial biomass crops on regional climate (Osborne et al., 2009), and its feedback in turn on the planted crop. However, such coupled models that integrate climate dynamics and biomass crop processes have been lacking. Prior modeling approaches have included the effect of land surface albedo change (Georgescu et al., 2011) but not the impact of altered biomass partitioning on surface temperature and ET. A fully coupled model overcomes this limitation, enabling more accurate quantification of the feedbacks (Betts, 2005; Osborne et al., 2009).

Climate alterations of large-scale land use changes may have further impacts on other annual crops in the region of interest. Corn and soybean are, respectively, the first and fourth most productive crops, in terms of tonnes of grain produced globally. Adapting US agriculture to climate change is critical to global food and energy securities, since it currently produces more than 33% of the world's corn and soybean (FAO, 2021), most of which is grown in the Midwest Heartland. Is the expansion of biomass crops on marginal land a possible climate adaptation strategy for US agriculture? How would land use induced changes in ET, sensible heat, and surface albedo impact regional temperature and rainfall? How would the resulting regional climate changes impact the biomass crop itself? To answer these questions, we developed a fully coupled modeling system that represents the two-way interactions between crop and climate on an hourly basis. The modeling

system was further applied to study how a large-scale planting of productive biomass crops on marginal land could impact the regional climate and the overall crop yields.

2 | MATERIALS AND METHODS

Here, we couple a mechanistic crop growth model (BioCro) (Miguez et al., 2012) with a regional Climate-Weather Research and Forecasting model (CWRf) (Liang et al., 2012) to account for the two-way interactions between the crop and climate systems. BioCro, driven by CWRf-predicted climate conditions, simulated C4 photosynthesis, light interception, dynamic biomass partitioning, and growth for *Miscanthus × giganteus* (*Miscanthus*) and connected back with the land surface and subsequent climate processes of CWRf (Figure S1). Before coupling, the original BioCro was modified to achieve better performance and physiological representation of *Miscanthus*. The coupled model described the crop production and water use dynamics, interacting with the climate on an hourly basis at a $30 \times 30 \text{ km}^2$ grid size over the contiguous United States.

Three simulation experiments were conducted for the years from 1980 to 2019: control, one-way, and two-way. The control simulation is the default CWRf stand-alone integration with the initial and boundary conditions derived from the European Centre for Medium-range Weather Forecasts 5th generation reanalysis (Hersbach et al., 2020). The one-way simulation estimated *Miscanthus* growth using BioCro driven by the control CWRf climate outputs. The two-way simulation used the fully coupled CWRf-BioCro to predict both climate and plant growth interaction for each hour of the year at each location (Figure 1). In both one-way and two-way experiments, the improved BioCro (see 2.1 and 2.2) was consistently used to simulate *Miscanthus* growth, replacing the current vegetation on marginal land.

We selected two marginal land use (MLU) scenarios, as mapped previously (Cai et al., 2011), to approximate the range of impacts on the regional climate and the subsequent contribution to biomass production due to feedback: (1) MLU1 consists of mixed crop and natural vegetation land with marginal productivity; and (2) MLU2 adds to MLU1 with degraded or low-quality cropland, some portion of grassland, savanna, and shrubland, but excludes the total pasture land for animal production. The absolute area of each grid point was converted to the relative fraction of that grid point that classified as MLU1 and MLU2 for model calculations. Given the common use of BioCro and MLU, all differences between the one-way

and two-way simulations in climate and productivity are solely due to climate feedback on the crop.

The local and teleconnected effects of the above land use change were investigated for the Heartland of US agriculture in the Midwest and Southern regions. The Midwest includes the 12 major agricultural states of the Corn Belt while the Southern includes eight central-eastern states of the Cotton Belt (Figure S2).

Comparing the control (i.e., existing vegetation of the marginal land) and two-way simulations, we showed how changing vegetation to *Miscanthus* could impact the regional climate, including ET, sensible heat, VPD, surface temperature, and precipitation, which could also affect crop growth conditions across the Heartland. Comparing the one-way and two-way simulations, we quantified the impact of the altered climate on the predicted *Miscanthus* harvestable biomass across the marginal land.

Prior to running the above simulations, we used the *Miscanthus* predictions from the one-way simulation to first calibrate the biomass partitioning parameters and then validate annual yields against observations at multiple independent sites across the US region.

2.1 | BioCro improvements and validations for *Miscanthus*

Several changes were made to the original *Miscanthus* BioCro (Miguez et al., 2009, 2012) before coupling with CWRf for simulating the growth of *Miscanthus* in both the one-way and two-way simulations. First, the biomass partitioning scheme for each organ was changed from a calendar-based table to logistic functions (Osborne et al., 2015) for all the growth stages of *Miscanthus* except emergence, where carbon stored in the rhizome is mobilized to drive the initial growth of the new season's shoots and roots. Secondly, the rate of leaf senescence rate was estimated by taking the maximum of three values (APSIM, 2021) predicted by (1) aging of leaves determined from the accumulated thermal time, (2) light competition, and (3) frost-induced senescence.

Observed biomass of leaf, stem, root, and rhizome records (Dohleman et al., 2012; Heaton, 2006) were used to determine the partitioning coefficients (Figure S3a), and the optimized parameters for partitioning were obtained using an R package *dfoptim*. These newly calibrated biomass partitioning coefficients together with the corresponding parameters are shown in Table S1. After calibration, the model performance was further evaluated (Figure S3b) using the observed stem biomass data (Table S2) from multiple independent sites and years across the United States (LeBauer et al., 2018). The model performance was estimated with a root mean square error

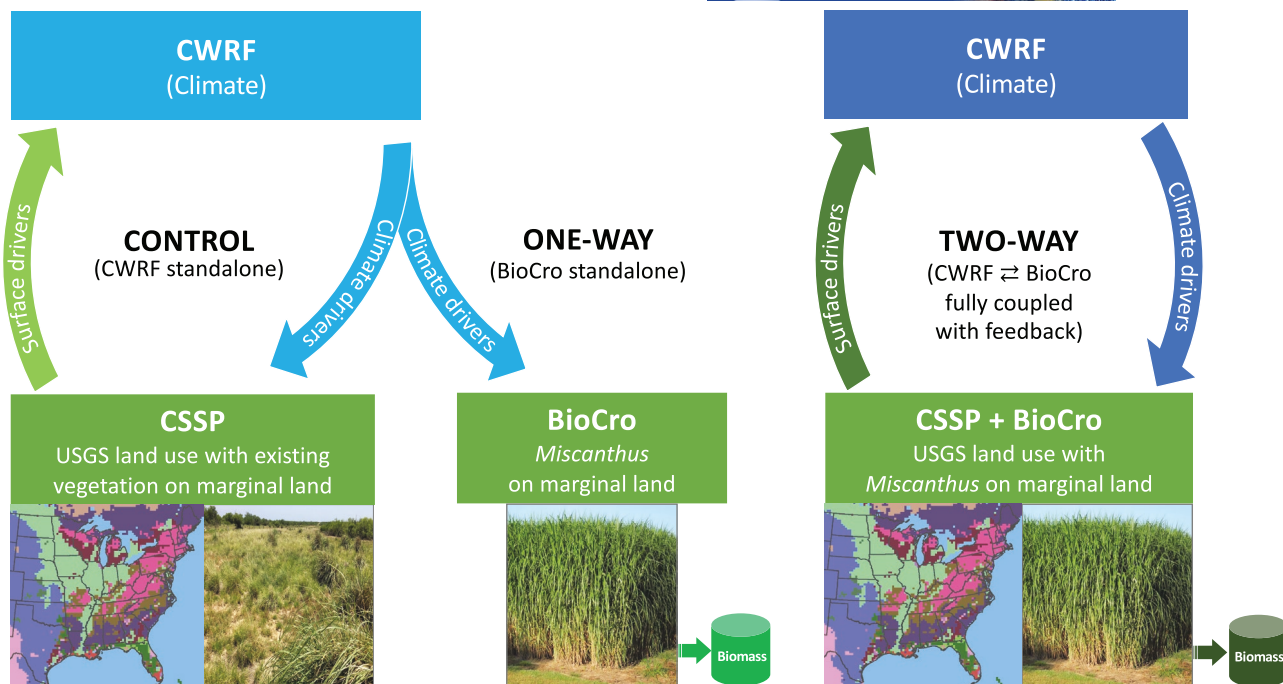


FIGURE 1 Experiment design comparing the control, one-way, and two-way simulations using the climate (CWRf) and crop (BioCro) stand-alone and coupled models. The CWRf has a built-in Conjunctive Surface-Subsurface Process (CSSP) module to incorporate the full surface-atmosphere interaction for climate prediction. The control experiment is the stand-alone CWRf simulation based on USGS' land use categories distributed over the United States, which include the existing natural vegetation on marginal land. The one-way run is the stand-alone BioCro simulation for *Miscanthus* growth on marginal land as driven by the climate conditions from the control CWRf simulation. The two-way experiment is the fully coupled CWRf-BioCro simulation for growing *Miscanthus* on marginal land while keeping all others identical to the control experiment. *Miscanthus* production is estimated by BioCro in the one-way and two-way simulations. The one-way simulation takes the CWRf climate drivers, including precipitation, 2-meter temperature, surface radiation, relative humidity, and wind speed, as the input conditions for *Miscanthus* to grow on marginal land without feedback onto the climate. The two-way simulation accounts for this feedback, in which the key surface characteristics or drivers for *Miscanthus*, including leaf area index (LAI), root fraction, albedo, and roughness, differ significantly from the existing vegetation on marginal land and hence are expected to simultaneously alter the regional climate and biomass production. The flow arrow depicts the direction of driving, while different colors distinguish varying state conditions

(RMSE) of about $6.4 \text{ t ha}^{-1} \text{ year}^{-1}$ and a concordance correlation coefficient (CCC) of 0.68 for 17 field trial locations, which is comparable to those (RMSE = $8 \text{ t ha}^{-1} \text{ year}^{-1}$ and CCC ~ 0.86) of the previous *Miscanthus* modeling study (Miguez et al., 2012), even though several more sites were used in our validation (Figure S3).

2.2 | Development of the coupled CWRf-BioCro model

In the coupled model system, the land surface part of CWRf was modified to incorporate the two MLUs (Cai et al., 2011) for growing biomass crops. A weighting procedure, based on the MLU fraction in each cell, was added to generate combined surface quantities that feedback on the atmosphere. The performance of CWRf climate alone has been rigorously evaluated in previous studies (Liang et al., 2012; Sun & Liang, 2020), which include comprehensive

comparisons with other community-based regional climate models. For the purpose of this study, we focus on the modifications of model components related to BioCro to achieve better model performance, computational efficiency, and representation of *Miscanthus* at the regional scale.

2.2.1 | CWRf physics schemes and land use

The CWRf (Liang et al., 2012) is a significant modification of the Weather Research and Forecasting Model (WRF) based on NCAR's Advanced Research WRF (ARW) framework. The CWRf model structure is the same as WRF, of which the software architecture and physics representation are fully documented (Michalakes et al., 2005; Skamarock et al., 2008). Table S3 summarizes the key model and physical configurations for the CWRf-BioCro simulations presented in this study.

Radiation and hydrology are two of the key driving processes that affect crop growth. To better represent them, we used CWRf's physically based schemes to replace BioCro's default calculations. For ground surface solar insolation, BioCro's original algorithm, which assumed constant atmospheric transmittance and scattering coefficients for photosynthetically active radiation, was replaced with CWRf's four-band (i.e., direct/diffuse and visible/near-infrared) radiation scheme. The cloud-aerosol-radiation ensemble modeling system built in CWRf provides a superior simulation of radiative fluxes (Liang et al., 2012; Liang & Zhang, 2013). For hydrology, BioCro's simple bucket model was replaced with CWRf's more advanced three-dimensional soil moisture transport model, known as the Conjunctive Surface-Subsurface Process (CSSP) model (Choi et al., 2013). The CSSP incorporates a detailed solution for vertical and lateral transport of soil moisture and water flow. It has been well calibrated and validated in previous studies (Choi et al., 2013; Yuan & Liang, 2011). It ensures a more reliable estimation of the monthly variations on soil moisture, ET, surface and subsurface run-offs, and soil water table. These hydrological predictions are crucial for the estimation of the water-related biophysiological variables, particularly water stress effects on crop growth and development.

The dominant land cover types in CWRf used the United States Geological Survey (USGS) 24-categories (Figure S4a) in the control experiment's configuration. *Miscanthus* growth was only simulated on the marginal land (Figure S4b), which occupies only a fraction of model grids. If a grid point had a significant proportion of marginal land area ($\geq 1\%$), BioCro was called to calculate the crop dynamic growth and the hourly updated leaf area index (LAI), which was passed to CSSP to calculate the land surface quantities (Figure S5). The key quantities include surface albedo, heat fluxes, soil moisture, and temperatures. Finally, a weighting procedure of the land surface quantities between the remaining vegetation, as defined by USGS, and *Miscanthus* was performed and the weighted quantities from each grid point were passed to the atmospheric modules of CWRf (Figure S5).

2.2.2 | Stomatal conductance

The Ball-Berry model was used to calculate the stomatal resistance in BioCro (Collatz et al., 1992). A fixed-point iteration approach was used by default in the model to find the equilibrium between photosynthetic assimilation, leaf temperature, and stomatal conductance, which can generate non-convergent results. Convergence was obtained by using the Newton-Raphson method (Sun et al., 2012) to

ensure numerical stability of the coupled CWRf-BioCro model in solving the equilibrium of stomatal conductance.

2.2.3 | Root distribution

To represent the root distribution of *Miscanthus* in the model, we fitted the observed root biomass data to a logistic function as follows (Schenk & Jackson, 2002),

$$f = \frac{R_{\max}}{1 + \left(\frac{x}{D_{50}}\right)^c}$$

where f is the total biomass above soil depth x . $R_{\max}$, D_{50} , and c are three parameters to be optimized against observations. $R_{\max}$ is the total biomass for a given root profile, D_{50} is the soil depth where the total biomass above is half of $R_{\max}$, and c is a dimensionless shape parameter.

We used the least square method to find a set of the parameters that minimize the RMSE of the model estimate from the observed data (Black et al., 2017). Observational data were taken from all 24 sample repetitions of the five bulk soil layers (see Table S4) for a year, which generated about 120 samples after excluding the invalid data.

The observed *Miscanthus* was planted in 2009 and the root mass of the mature stand was measured in 2014 (Black et al., 2017). Figure S6a shows the fitting results against observations. There is a large variation of the root biomass, which ranges from 300 to over 1200 g m⁻². Ninety-five percent of the root mass fraction was in the top 3 m (Figure S6b). Similar results of such deep rooting of *Miscanthus* have been reported in previous studies (Black et al., 2017), which is a key factor that determines the crop's high water use efficiency and productivity.

2.2.4 | Phenology

BioCro assumes that the starting and ending time of the growing season at a given location are determined by searching for the first day of the year where air temperature is over 0°C at all hours of the day. However, this algorithm works only if and when the whole year's temperature record is known before running the CWRf-BioCro model. This is viable for the one-way modeling where the historical driving forces are given in advance. To determine the starting and ending day of year (DOY) for growing seasons in the two-way modeling where the temperature is to be predicted, the dates were estimated by using the control's three-hourly temperature records and calculating the expected value (i.e., weighted mean by frequency) of multiple years' DOYs. This simple method

generated a growing season period that had a realistic spatial variation (Figure S7) in distinguishing cold and warm climate regions.

Once senesced at the end of the growing season, stands will progressively lose dead biomass through fragmentation. Heaton (2006) recorded an average loss of $0.07 \text{ t ha}^{-1} \text{ day}^{-1}$ for *Miscanthus*. In practice, the harvest is usually in the early spring and thus March 1 was used in our simulations. Therefore, for each location, the number of days for senescence was calculated from the last day of the growing season to the harvest date. A grid point is discarded if the harvestable biomass became negative.

Miscanthus is a perennial that usually requires four to five annual growth cycles after planting to reach maximum annual yield. We conducted a 4-year spin-up simulation from 1980 to 1983 by using the CWRP control's climate forcing data. Starting with an initial planting biomass of 0.3 t ha^{-1} , the spin-up simulations allowed the rhizome, as perennating organ, to be carried over from each preceding year. After 4 years of accumulation, the resulting rhizome biomass (Figure S8) predicted for 1983 was saved and used as the initial state for the one-way and two-way long-term simulations. Note that some warmer areas to the far south are ignored, because sustainable cultivation of *Miscanthus* would not be possible at locations where the first frost day occurs after DOY of 330, since this is an inadequate signal for remobilization of biomass reserves to the rhizome for regrowth of the next year.

2.3 | Seasonal climate and biomass data analysis

The following datasets can be accessed from a public repository (He, 2021), (1) all seasonal (spring, summer, autumn, and winter) climate and surface data for the control and two-way simulations (MLU1 & MLU2) from 1980 to 2019, including 2-meter temperature, precipitation, ET, latent and sensible heat, VPD, albedo, LAI, soil moisture content, runoff, and leaf and stem biomasses; (2) total harvestable biomasses accumulated across the marginal land for the two-way and one-way simulations (MLU1 & MLU2) for each year of the 40-year period. Statistical significance tests based on the *t*-test at a *p*-value level of 0.05 were applied to all long-term averages of differences at each grid point, either between two-way and control for climate variables or between two-way and one-way for the biomasses. Spatial averages were then calculated based on the region of interest, including the Midwest and Southern Heartlands, each federated state, and marginal land with land fraction >0.1 .

2.4 | Ethanol and carbon offset calculations

As an example of biomass products, we analyzed cellulosic ethanol, but recognize many other emerging uses of bioproducts derived from ligno-cellulosic material (Jones, 2021). We used a conversion efficiency of 282.2 L Mg^{-1} biomass of 15% moisture content to calculate the cellulosic ethanol yield from *Miscanthus* (Dwivedi et al., 2015). To calculate the soil carbon sequestration, we assumed $1.62\text{--}1.82 \text{ Mg C ha}^{-1} \text{ year}^{-1}$ as measured for *Miscanthus* grown on low-quality soils in Illinois and Indiana (Dwivedi et al., 2015). Calculations of the net CO_2 offset due to the displacement of fossil fuels were based on the total ethanol volume (Table S2), GHG intensity of $94 \text{ g (CO}_2\text{) MJ}^{-1}$ for gasoline, and -37 to $-59 \text{ g (CO}_2\text{) MJ}^{-1}$ for cellulosic ethanol from *Miscanthus* grown on low-quality soils (Dwivedi et al., 2015).

3 | RESULTS

3.1 | *Miscanthus* on marginal land benefits the Heartland climate

An important aspect of the model prediction is the spatial pattern of the regional climate responses to the simulated land use change. The gridded fractions of the two MLU scenarios represent total areas of 43 and 123 Mha, respectively, where the existing vegetation (USGS 24-categories Figure S4a) is converted to growing rainfed *Miscanthus* (Figure 2a). This decreases the long-term (1980–2019) summer mean temperature averaged across the Midwest Heartland by 0.23°C for MLU1 and by 0.56°C for MLU2 (Figure 2b). In the Southern Heartland, a similar cooling effect is predicted, largely north of the Gulf Coast states, averaging 0.27°C for MLU1 and 0.39°C for MLU2 (Figure 2b). A cooling impact of about 1°C is predicted in the main corn–soybean cropping areas for MLU2, primarily in the Midwest, with magnitudes varying significantly among states (Figure 3).

The average summer precipitation in the Midwest is significantly increased by 23 and 29 mm or 14% and 15% for MLU1 and MLU2, respectively (Figure 2c). In the Southern Heartland, the increase is smaller at 13 and 8 mm, but remains high in proportion to current precipitation at 14% and 16% (Table S1). The precipitation changes vary spatially, with increases of up to 57 mm in parts of the central and western Midwest, and with some small decreases on the eastern edge and to the south of the Heartland (Figure 2c). Unlike the temperature changes, which are greatest in the areas with the largest amounts of *Miscanthus* (Figure 2a), the precipitation changes

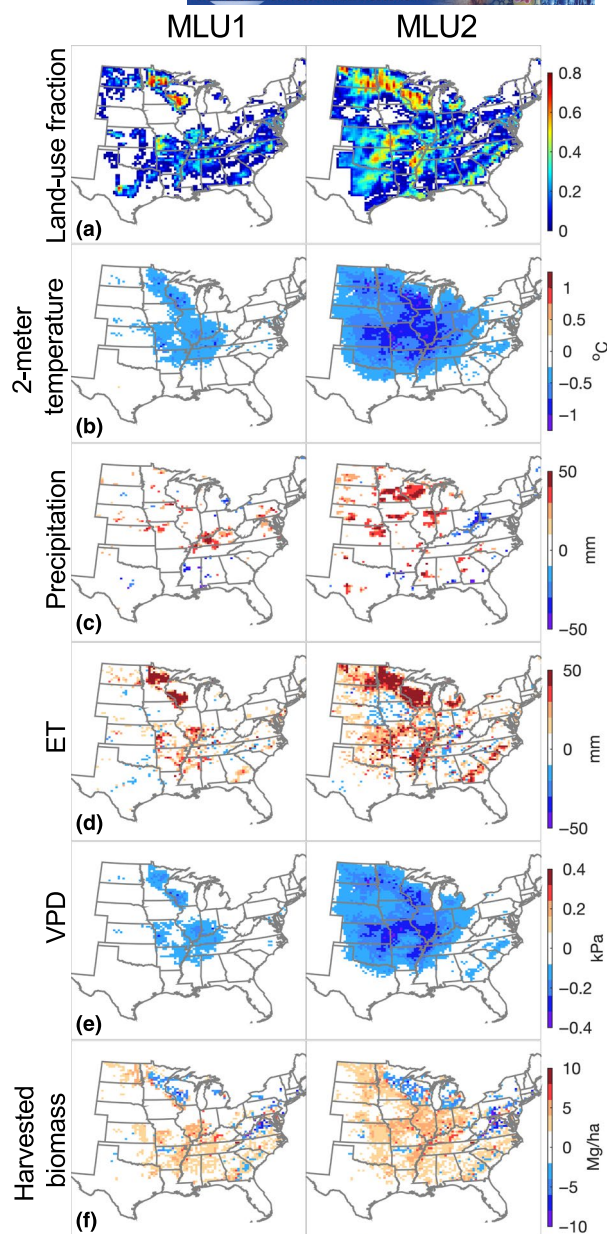


FIGURE 2 Predicted impacts of including the land-atmosphere interactions on the summer climate and the biomass yield for two MLU scenarios. (a) The marginal land fractions based on the CWRf's $30 \times 30 \text{ km}^2$ grids for the two MLU scenarios. (b–e) Mean climate differences between the control (i.e., no vegetation change) and presence of *Miscanthus* on the 43 and 123 Mha of marginal land represented by MLU1 and MLU2, respectively. Climate differences are for the summer (June, July, and August) averaged from 1980 to 2019. This uses the two-way approach which accounts for feedback of climate change on the planted *Miscanthus*. Climate variables are (b) 2-meter air temperature ($^{\circ}\text{C}$), (c) precipitation (mm), (d) evapotranspiration (ET, mm), and (e) vapor pressure deficit (VPD, kPa). (f) The difference in *Miscanthus* stem biomass yield (Mg ha^{-1}) resulting from this climate change by subtracting the one-way (i.e., no feedback) predicted yield from the two-way. All colored grid points passed the t -test at a significance level of 0.05 for the 40-year period

can occur hundreds of miles beyond these areas due to teleconnections resulting from mesoscale atmospheric circulations. This causes both increases and decreases depending on location (Figure S9). However, in the major areas of food and feed production in the Heartland, precipitation is predominantly increased (Figure 2c).

The changes in ET and VPD are inverse, following a similar pattern of spatial change as temperature (Figure 2d,e). ET increase is greatest during the summer because *Miscanthus* grows a larger leaf canopy than the current vegetation on marginal land of the control case. This results in a transfer of more soil moisture to the atmosphere, increasing the humidity above the canopy. Consequently, the summer VPD is reduced by 0.06 and 0.15 kPa or 5% and 13%, respectively, for MLU1 and MLU2 as averaged across the entire Midwest, and by about half of these amounts in the Southern Heartland. For both MLU scenarios, the soil moisture of the top 1 m is only slightly reduced with large spatial variations in both regions (Table S5) despite the simulated 40-year continuous cultivation of *Miscanthus* on the marginal land.

These regional temperature and precipitation changes result from local feedback and teleconnection through complex processes involving many climate- and crop-related variables. Despite such complexity, there is a distinct difference in the multivariate correlations of these variables between grid points on the marginal land (ML) and non-marginal land (non-ML). On the non-ML, the interactions among the soil, land surface, and atmosphere processes follow a conventional mechanism of land surface models in CWRf. Overall, the variables are thus expressed in a highly correlated manner. By contrast, on the ML where a proportion is now used for growing *Miscanthus*, a different biophysical process is introduced by the growth mechanism of BioCro. New processes in the system thus reduce the linear correlations among variables on the ML (Figure S10). Furthermore, on the ML uncertainties are associated with the land use fraction, that is, the smaller the fraction is, the more uncertain the direction of change can be. For example, the latent heat exchange with atmosphere is consistently increased for grid points with large fractions of *Miscanthus* use but can decrease where the fraction becomes smaller; this pattern applies to the sensible heat exchange but with an inverted direction of change (Figure S11).

The average growing period of *Miscanthus*, in the Midwest, spans from April to October. Thus, the climatic impacts occur beyond the summer (JJA, Figure 2), affecting the spring (MAM) and autumn (SON) but with a weaker magnitude (Figure S12). In spring, a cooling pattern appears in the Southern marginal land where the crop emerges first because of higher growing degree days.

FIGURE 3 Predicted summer (JJA) temperature reductions ranked for the states of the two agricultural Heartland regions (Midwest and Southern). This assumes replacing the existing vegetation of the 123 Mha of marginal land in scenario MLU2 with *Miscanthus*. Shown values are the mean reduction in surface 2 m air temperature (+1 standard deviation) averaged over all grid points within each state

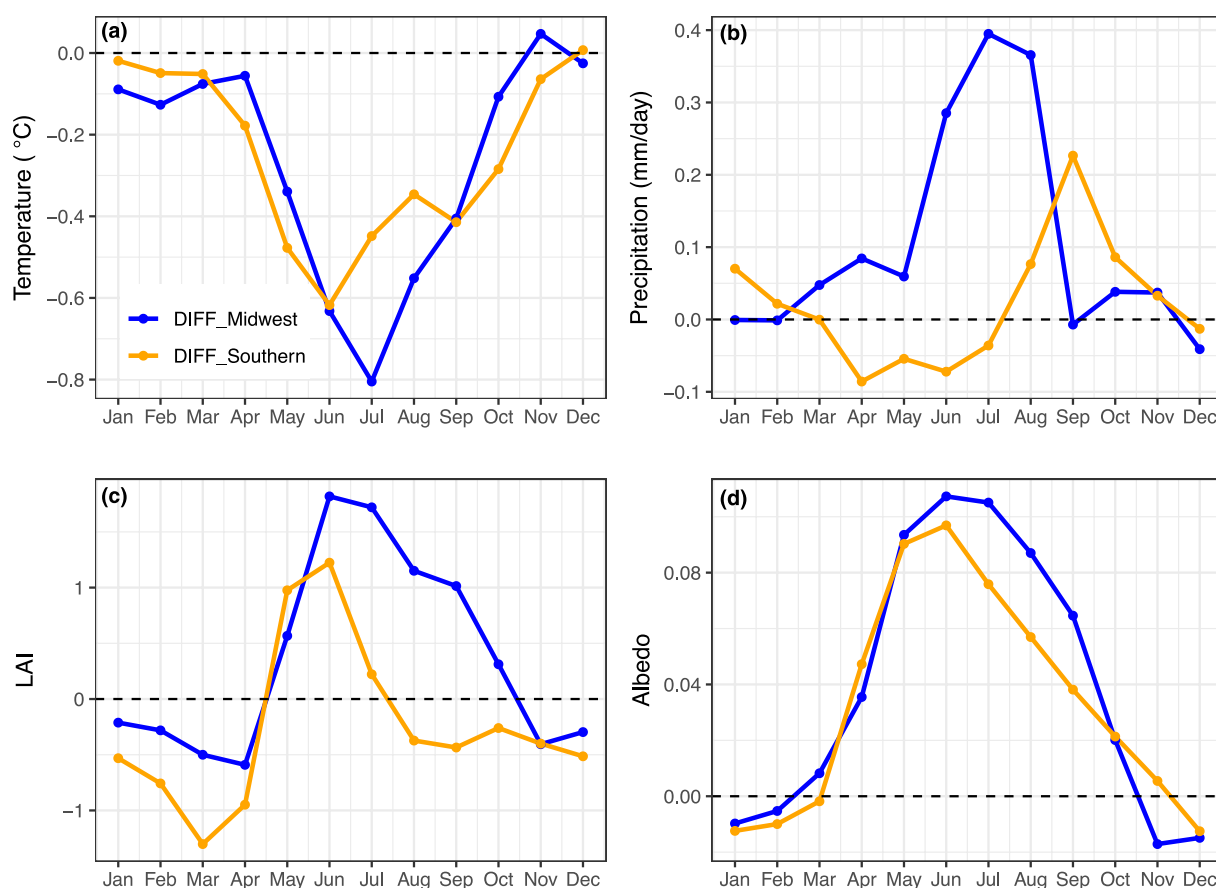
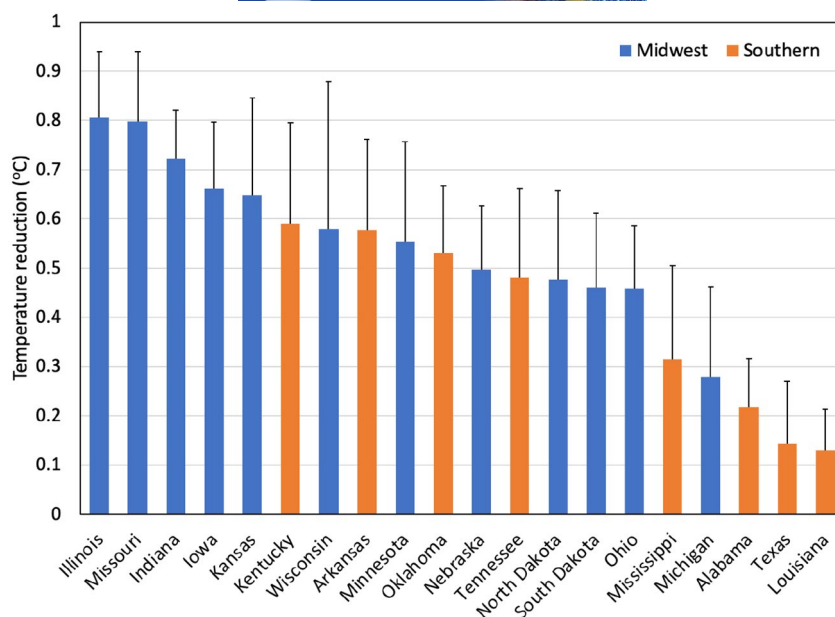


FIGURE 4 Annual cycles of the difference between the MLU2 two-way and the control runs in key variables averaged over the two Heartland regions simulated for the period 1980–2019: (a) Two-meter temperature above ground (°C); (b) Precipitation rate (mm day⁻¹); (c) Leaf area index (LAI); and (d) Albedo. All variables were tested by a significance level of 0.05 and were averaged for each region at grid points with marginal land fractions >0.1

The cooling effect is most significant in summer and becomes weaker in autumn (Figure S12). The precipitation increase emerges in spring, peaks in summer, and remains

strong throughout autumn (Figure S12). The seasonal changes in the key variables (temperature, precipitation, LAI, and albedo) averaged over the Midwest and Southern

Heartland are further shown by the monthly means of annual cycles (Figure 4) for MLU2, where the changes during the summer are the most pronounced. The LAI of *Miscanthus* is modeled to be small in winter, causing a lower albedo than the existing vegetation. Similar annual cycles are found for MLU1 except for a smaller magnitude in the temperature reduction (Figure S13) due to a smaller land area simulated for planting *Miscanthus*.

3.2 | Two-way crop–climate feedback benefits *Miscanthus* production

The combined effect of reduced surface temperature and VPD with enhanced rainfall and ET resulted in mostly increases in the total harvested dry biomass of *Miscanthus* for both MLU scenarios in the two-way simulation, when compared with the one-way (Figure 2f). Across the marginal land, the positive feedback captured by the two-way coupled simulation predicts 4% and 7.5% more *Miscanthus* total yield (t year^{-1}) for MLU1 and MLU2, respectively (Figure S14). These equate to additional biomasses of 27 ± 10 on MLU1 (43 Mha) and $128 \pm 21 \text{ Mt year}^{-1}$ on MLU2 (123 Mha).

The two-way and one-way coupling methods differ conceptually in the representation of how growing *Miscanthus* on marginal land affects regional climate and biomass production (Figure 1). Compared with the current vegetation of the marginal land, *Miscanthus* significantly alters the land surface properties by increasing LAI, and thereby evaporative surface, surface albedo, and surface roughness. These surface modifications cause significant changes in moisture and energy fluxes from the land to the atmosphere, which are not accounted for in a one-way coupling. The two-way coupling predicts these flux changes to affect not only the crop and soil processes but also the atmosphere. Growing *Miscanthus* on marginal land could increase ET (and latent heat flux) and decrease sensible heat flux. These flux perturbations are large enough to cause significant surface air cooling and more precipitation locally and also remotely by teleconnection through mesoscale circulation changes, especially in summer (Figure 2). Both the cooling and wetting effects cause a positive feedback that contributes to enhanced carbon fixation by *Miscanthus* photosynthesis and thus produce higher biomass yields (Figure S14). The correlation of interannual variation between the total biomass yield over all marginal land areas and summer temperature is strongly negative ($r = -0.63$ and -0.64 with $p < 0.01$ in MLU1 and MLU2). The corresponding correlation with summer precipitation is strongly positive ($r = 0.62$ and 0.59 with $p < 0.01$). Thus, a cooler and/or wetter growing season favors more biomass growth. These

two climate variables combined can explain 47% (MLU1) and 46% (MLU2) of the biomass interannual variance resulting from multivariate linear regressions.

4 | DISCUSSION

4.1 | *Miscanthus* ameliorates climate change impacts on crop productivity in the Heartland

Planting high productive perennial grasses on marginal land and in strips on sloping land prevents erosion, decreases nitrogen losses, and increasingly now provides an economic crop to meet the increased demand for bioproducts and biofuels (McCalmont et al., 2017; Schulte et al., 2017). Here, we show another distinctive advantage, amelioration of climate in the US Heartland. Using a mechanistic crop growth model coupled with a regional climate model, planting *Miscanthus* on 43–123 Mha of marginal land lowers the Midwest summer temperature by $0.5\text{--}1^\circ\text{C}$, with cooling across most of the eastern half of the United States (Figure 2b). This magnitude of cooling would substantially offset the regional warming that is projected at about $2\text{--}3^\circ\text{C}$ by mid-21st century (Byun & Hamlet, 2018; Masson-Delmotte et al., 2021). It also projects a significant summer cooling for key urban areas (Figure 2b), including Chicago, which are suffering more frequent extreme heat events (Jones et al., 2015). Meanwhile, precipitation in much of this region would be increased by this planting of *Miscanthus* or similar perennials (Figure 2c). An analysis of United States-observed interannual variations (Lobell & Asner, 2003) showed that per 1°C of cooler summer temperature anomalies caused corn yields to increase by $1.31 \pm 0.09 \text{ t ha}^{-1}$ and soybean yields by $0.38 \pm 0.03 \text{ t ha}^{-1}$. On this basis, the temperature decreases from growing *Miscanthus* on marginal land (MLU2) as reported here would amount to increases of 13% in corn yields and 12% in soybean yields, a hugely significant apparent co-benefit for the staple crops of the Heartland. Such an amelioration of temperature change could save at least one-third of the previously projected yield losses resulting from climate change projected at 30% for the Midwest by 2050 (Lobell et al., 2014; Zhou et al., 2021). Given the background of projected global climate change, planting *Miscanthus* or other productive perennial grasses on marginal land could provide important futureproofing of crop yields in the Heartland of great significance to global food security (Deryng et al., 2014), while providing biomass for renewable fuels and products, in addition to increased soil carbon storage (Davis et al., 2012).

We show that planting *Miscanthus* on 123 Mha of marginal land (MLU2) causes an average cooling of 0.56°C

in the Midwest, approaching 1°C in the central states of Illinois and Missouri. Since MLU2 contains only 54 Mha in the Midwest, our result contrasts to a previous study (Georgescu et al., 2011) where planting biomass crops over the entire Corn Belt, including both the existing arable staple cropland and uncultivated marginal land (~84 Mha), would lead to an average cooling of 0.51°C. That study, however, considered only changes in surface properties (i.e., albedo, LAI, and vegetation fraction) without the feedback between the crop and climate. Another study (Wang et al., 2017) that used empirical representations on the surface properties and the same MLU as MLU2 for growing *Miscanthus*, but without the coupled feedbacks of the present study, reported a cooling potential of 1–2°C in the Midwest and up to 5°C in the Great Plains, much larger than the prediction here, particularly in the mountainous regions. In a much closer agreement with our prediction was an observational analysis (Loarie et al., 2011b), where the measured effect of replacing marginal mixed cropland and pastureland in Brazil by sugarcane, similarly a perennial and a close relative of *Miscanthus*, resulted in a measured regional cooling of 0.9°C. In the Southern Heartland, the cooling effect is weaker, averaging 0.29°C (Table S5; Figure 2c). This is because *Miscanthus* growth under these warmer conditions enters senescence much earlier in the warmer Gulf States. Energycane, a productive perennial, more adapted to warm conditions may provide greater benefit if planted on marginal land in these states (Duval et al., 2015). Across the whole Heartland, the precipitation increase due to planting *Miscanthus* compensates for the larger ET loss, which results in a nearly negligible change in regional mean soil moisture (SM₁₀₀ in Table S5; Figure 2c). Soil water can even increase in some areas where the precipitation gain exceeds the ET loss. Growing *Miscanthus* on marginal land also reduces VPD in the Heartland (Figure 2e), significantly counteracting the projected 20% increase under climate change over the next 40–50 years in the region (Lobell et al., 2014; Ort & Long, 2014).

The overall feedback through the climate–crop interaction from growing *Miscanthus* on marginal land is beneficial to both regional climate and biomass yield. The feedback is predicted to be positive in most areas due to cooling, lowered VPD, and increased precipitation. The benefit extends well beyond the marginal land growing *Miscanthus* to other parts of the Heartland and beyond (Figure 2). Therefore, *Miscanthus* deployment on marginal land is expected to be beneficial for a broader scale of crop production in the teleconnected regions. Although not included in these simulations, it could be expected that strips of *Miscanthus* or similar perennial grass biomass crops grown within corn–soybean fields to arrest erosion (Schulte et al., 2017) would have similar climate benefits.

4.2 | Contribution to net-zero carbon emissions

One of the goals established at the 26th Conference of the Parties (COP26) meeting was to secure global net-zero CO₂ emission by 2050 and keep the 1.5 degrees rise within reach (COP26, 2021). Our study shows that *Miscanthus* on marginal land can be one nature-based solution that the United States can scale up to contribute to global efforts of meeting the goal of net-zero emission. Production of cellulosic ethanol from *Miscanthus* has already been shown to be a carbon-negative biofuel (Dwivedi et al., 2015). Considering the two-way climate–crop feedback shown in this study, the total *Miscanthus* productivity may be larger than previous estimations, allowing a further increase in the efficiency of carbon reduction. The two-way feedback predicts a greater volume of potential cellulosic ethanol of 9.2 and 42.2 billion liters or 4.0% and 7.5%, respectively, for MLU1 and MLU2 (Table S6). This suggests that the CO₂ offset resulting from the displacement of fossil fuels by, for example, cellulosic fuels based on *Miscanthus*, was significantly underestimated in previous studies that did not include the climate feedback (Davis et al., 2012; Hudiburg et al., 2016).

Growing *Miscanthus* in MLU1 and MLU2 could accumulate an additional 0.069–0.078 and 0.199–0.223 Pg of soil carbon per year based on the estimated rate of carbon sequestration (Dwivedi et al., 2015), respectively. The soil carbon sequestration is sufficient to compensate in 7–21 years for the 1.4 Pg carbon loss caused previously from historical plowing the A-horizon layer of the Corn Belt (Thaler et al., 2021). Moreover, we estimate an annual net CO₂ offset of 0.66–1.77 Pg through the displacement of gasoline usage and accounting for all steps in the production of cellulosic biofuels (Table S6; Methods 2.3). Greater gains may be expected from using the biomass to replace nonrenewables, such as plastics (Jones, 2021). Hypothetically, if all of the land in MLU2 was used for *Miscanthus*, then the additional biomass resulting from climate feedback alone, which was omitted in previous studies, would be sufficient to produce additional fuel volumes approximating to 132% (Table S6) of the renewable fuel standard (RFS) original mandate of 32 billion liters by 2022 (Hudiburg et al., 2016).

4.3 | Implications on wider applications of the coupled model system

In this study, we have developed a fully coupled system of a regional climate model and a crop model. Although the results in the paper are specific to *Miscanthus* in the United States, the general modeling approach and framework would be applicable to evaluate the climatic impact

of land use change for growing other crops that are critical for both regional and global food and energy securities. In fact, BioCro has already been or is under development for several other crops, including switchgrass, energycane, soybean, and willow (Lochocki et al., 2022; Matthews et al., 2022; Wang et al., 2015). With the coupled system of CWRP-BioCro, one could easily add new crops to simulate the impact of land use change on the regional climate and crop productivity for both retrospective and future climate scenarios. Furthermore, this multi-crop system would allow us to optimization of the geo-allocation of a combination of perennials and annual crops for various adaptation goals such as maximizing yields, minimizing water uses, and moderating the adverse effects of climate change. For example, while *Miscanthus* is not suitable to grow in the Gulf Coast region, energycane has been found productive in the area (Duval et al., 2015) and while *Miscanthus* has poor yields in cold climates, willow would be suitable (Larsen et al., 2016). Globally, the large availability of underutilized grazed pastureland (2.2 billion ha) contributes to merely 1% of global dietary energy (Monteiro et al., 2020). These lands have intensification potentials enough to make room for both food and energy crops. This would make the application of our coupled modeling framework particularly interesting to evaluate the global implications of growing perennials such as *Miscanthus* in the context of sustainable development, climate change mitigation, and adaptation.

5 | CONCLUSIONS

To achieve the climate and crop production benefits of growing perennials on MLU at such a large scale first requires analyzing economic, ecological, and societal impacts (Calvin et al., 2021). For example, large-scale expansion of bioenergy is often criticized because economic models predict that a direct competition of land use between food and energy crops would raise food price (Xie et al., 2019), which, however, does not consider the indirect climate benefits of growing *Miscanthus* as shown in our study. A comprehensive assessment of all these aspects is undoubtedly challenging, but growing perennials on marginal land is one of the feasible solutions to mitigate climate change, providing bioenergy and bioproducts to replace fossil fuel use to help contain global warming within 1.5°C by 2050 (Welsby et al., 2021). Second, since *Miscanthus* has relatively few field trials in the United States, our model calibrated/validated against these limited data may contain nontrivial uncertainties in making the assessment over all marginal lands across the entire agriculture Heartland (Sharma et al., 2022). Future field trials of *Miscanthus* and other alternate biomass crops

covering broader regions will help reduce uncertainties. Finally, our predicted CO₂ offset assumes a successful commercialization of the second-generation cellulosic ethanol, which is yet to be seen despite demonstrated success at the laboratory and pilot scales.

The fully coupled model developed in this study has the potential to be applied to other climate regions and crop types. Our findings on *Miscanthus* have shown considerable potential for regional climate change mitigation, that will benefit current food and feed crops. Simultaneously, it would conserve soil, sequester carbon, and finding a potential productive use for large areas of marginal land to deliver biomass for energy and bioproducts.

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CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests.

AUTHOR CONTRIBUTIONS

Liang, He, Jaiswal, and Long designed the research; He, Jaiswal, Sun, and Liang developed the models and conducted the simulations; He, Jaiswal, Liang, and Long analyzed the results and wrote the paper.

DATA AVAILABILITY STATEMENT

All seasonal data used to generate the results in the manuscript can be downloaded freely from the data repository, He, Yufeng. 2021. "CWRP-BIOCRO COUPLING." OSF. May 4. <https://doi.org/10.17605/OSF.IO/A8MY7>. All data analysis code is available from the GitLab repository (https://gitlab.com/yufeng87/cwrp_biocro_post.git). The code of the coupled model is available from the corresponding author upon reasonable request.

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