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Landscape patterns of bioenergy in a changing climate: implications for crop allocation and land-use competition

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Abstract. Rural landscapes face changing climate, shifting development pressure, and loss of agricultural land. Perennial bioenergy crops grown on existing agricultural land may provide an opportunity to conserve rural landscapes while addressing increased demand for biofuels. However, increased bioenergy production and changing land use raise concerns for tradeoffs within the food–energy–environment trilemma. Heterogeneity of climate, soils, and land use complicate assessment of bioenergy potential in complex landscapes, creating challenges to evaluating future tradeoffs. The hypothesis addressed herein is that perennial bioenergy production can provide an opportunity to avoid agricultural land conversion to development. Using a process-based crop model, we assessed potential bioenergy crop growth through 2100 in a southern Appalachian Mountain region and asked: (1) how mean annual yield differed among three crops (switchgrass *Panicum virgatum*, giant miscanthus *Miscanthus* × *giganteus*, and hybrid poplar *Populus* × sp.) under current climate and climate change scenarios resulting from moderate and very high greenhouse gas emissions; (2) how maximum landscape yield, spatial allocation of crops, and bioenergy hotspots (areas with highest potential yield) varied among climate scenarios; and (3) how bioenergy hotspots overlapped with current crop production or lands with high development pressure. Under both climate change scenarios, mean annual yield of perennial grasses decreased (−4% to −39%), but yield of hybrid poplar increased (+8% to +20%) which suggests that a switch to woody crops would maximize bioenergy crop production. In total, maximum landscape yield increased by up to 90 000 Mg/yr (6%) in the 21st century due to increased poplar production. Bioenergy hotspots (>18 $Mg \cdot ha^{-1} \cdot yr^{-1}$) consistently overlapped with high suburban/exurban development likelihood and existing row crop production. If bioenergy production is constrained to marginal (non-crop) lands, landscape yield decreased by 27%. The removal of lands with high development probability from crop production resulted in losses of up to 670 000 Mg/yr (40%). This study demonstrated that tradeoffs among bioenergy production, crop production, and exurban expansion in a mountainous changing rural landscape vary spatially with climate change over time. If markets develop, bioenergy crops could potentially counter losses of agricultural land to development.

Key words: Appalachian Mountain region; biomass; climate change; giant miscanthus; hybrid poplar; land use; Miscanthus × giganteus; Panicum virgatum; Populus; *switchgrass.*

Introduction

Human population growth has placed increased demands for food, fiber, and fuel production on rural and semirural landscapes throughout the United States and Europe while simultaneously contributing to the conversion of agricultural lands to exurban development (Francis et al. 2012). The ability of rural and semirural landscapes to provide food, fiber, and fuel as well as conservation of natural and social heritage may be altered as climate warms and suburban and exurban development expands (Theobald and Romme 2007, Brown et al. 2010, IPCC 2013, Hatfield et al. 2014). Perennial biomass crops have emerged as an alternative agricultural land use to meet increased demand for non-fossil fuel-based energy (Powlson et al. 2005, Gopalakrishnan et al. 2009, Chen et al. 2011, U.S. Department of Energy 2011). Perennial biomass crops have received considerable support from governments at local, state, and country levels and are expected to play a large role in future energy production (Dale et al. 2014). Bioenergy, in the form of biomass crops, crop residues, and municipal wastes, currently provides 10% of the global primary energy supply (IEA 2014). Demand for bioenergy is expected to increase three- to 10-fold by 2050 in order to achieve reduced emissions goals in energy and transport sectors (IEA 2011, 2012). In semirural landscapes, bioenergy crop production may provide an opportunity to maintain agricultural landscapes and social heritage; however, it is difficult to assess this potential in

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landscapes with steep environmental gradients and complex land-use patterns.

Most assessments of bioenergy potential have focused on global and national scales (Cook and Beyea 2000, Campbell et al. 2008, Nair et al. 2012, Kang et al. 2014) or large industrial agriculture landscapes (Jain et al. 2010); few studies assess bioenergy production at a regionally relevant scale or consider local variation in soils, climate, topography, and land use (Field et al. 2008, Kukk et al. 2010, U.S. Department of Energy 2011). Changing climate conditions pose additional challenges on agricultural lands because current crops may have altered productivity in the future, and the viability of new options (such as bioenergy crops) is uncertain. Crop production will be affected by climate change in complex ways, depending on how individual crops respond to changes in atmospheric carbon dioxide concentrations, temperature, and precipitation (Hatfield et al. 2011). Elevated carbon dioxide concentrations contribute to increased plant growth and water use efficiency (WUE; e.g. "carbon fertilization effect"), but these gains may be offset by greater temperature or moisture stress (Hatfield et al. 2011). Global mean annual temperature is projected to increase by up to 4°C by 2100 and be accompanied by increased frequency of extreme events and greater climate variability (IPCC 2014). Across landscapes, crop responses will be complicated by heterogeneity in soils (e.g. increased soil respiration or texture-specific changes in soil moisture; Jasper et al. 2006, Whitby and Madritch 2013).

Crop models have been combined with climate scenarios to examine the vulnerability of agricultural production to changing climate patterns (e.g., Lobell and Field 2007, Challinor et al. 2010, Lobell and Gourdji 2012), but few studies have also considered changing land use and land-use competition (Hoogwijk et al. 2005, Schröter et al. 2005). In North America, increased development pressure threatens the persistence of rural landscapes and farmers can often realize substantial economic gains by selling their land (Olson and Lyson 1999). Removing farmland through development may alter a region's ability to adapt agricultural production to climate change (Fraser et al. 2011, IPCC 2014). In addition, exurban or urban development has wide-ranging impacts such as decreased water quality, increased invasive species presence, and biodiversity loss (Gavier-Pizarro et al. 2010, Radeloff et al. 2010, Webster et al. 2012).

Increased demand for bioenergy can provide an additional commodity for farmers and thereby may aid in farmland protection (Campbell et al. 2008, Fargione et al. 2009). Moreover, bioenergy crops provide additional benefits, including climate change mitigation and habitat for wildlife, and offer alternatives to row-crop agriculture (Dale et al. 2011*a*, Robertson et al. 2011, U.S. Department of Energy 2011, Blank et al. 2014). Bioenergy crop production that sustains rural landscapes may confer environmental benefits but is most likely to be successful if producers can harvest at levels that are able to maintain their livelihood (Dale et al. 2010). Increased bioenergy production may also increase competition for land (e.g. the "food, energy, and environment trilemma"; Tilman et al. 2009). Conflicts between food and fuel production may be alleviated by planting bioenergy crops on marginal lands, defined herein as land not currently used for food production (Gopalakrishnan et al. 2006, Campbell et al. 2008, Valentine et al. 2012, Gelfand et al. 2013).

The semirural landscapes of the southern Appalachian Mountains are identified as suitable for cultivating perennial bioenergy crops (Dale et al. 2011*a,b*, Nair et al. 2012, Behrman et al. 2013) and, typical of semirural landscapes in the eastern United States, have a long history of agriculture and timber harvest beginning in the late 1700s (Gragson and Bolstad 2006). Widespread agricultural abandonment began in the mid-1900s (Ramankutty and Foley 1999, Gragson and Bolstad 2006) and was followed by an increase in forest cover and expansion of exurban and suburban housing development (Wear and Bolstad 1998). Continued urbanization is expected to lead to declines in crop, pasture, and forested land within the region throughout the 21st century (Wear 2011). In contrast to the large industrial agricultural landscapes of the Midwest, biophysical complexity leads to steep gradients in soil and climate conditions, creating substantial environmental heterogeneity (e.g., Whittaker 1956, Turner et al. 2003) that influences land-use patterns and agricultural productivity. The extent to which perennial bioenergy crops may be agriculturally feasible across these complex and changing landscapes is unknown. Regional crop models that incorporate both climate scenarios and potential land-use competition provide a means for exploring potential bioenergy supply given alternate futures in biophysically complex regions with diverse land use patterns and drivers of environmental change.

Here, we assess potential bioenergy crop yield of switchgrass (*Panicum virginatum*), giant miscanthus (*Miscanthus* × *giganteus*), and hybrid poplar (*Populus* × sp.) in western North Carolina, USA under current climate and future climate scenarios resulting from medium to high emissions (e.g., IPCC representative concentration pathway [RCP] 4.5 and RCP 8.5). The three crops are suitable for biomass energy under current technologies, and are under research and development as biofuel energy sources. Under projected market expansion, the three crops are likely candidates for biomass production in the southern Appalachian Mountains and globally (Walsh et al. 2003, McLaughlin and Kszos 2005, Heaton et al. 2008). Other sources of biomass energy such as residues from annual crops and urban waste as well as forest biomass are possible in this region (U.S. Department of Energy 2011). We focus on the effects of biophysical complexity and climate change on perennial bioenergy crops to explore whether these crops have potential to augment the current crop portfolio in a diverse agricultural landscape. We used a process-based crop model and asked:

(1) How does potential mean annual yield differ among three perennial bioenergy crops under current and projected future climate in a complex, heterogeneous landscape? (2) How do maximum landscape yield, crop allocation, and the extent of bioenergy hotspots (areas with highest potential yields) vary among climate scenarios? (3) To what extent do bioenergy hotspots overlap with agricultural land at high risk of conversion to development?

Study area description

We used a 10-county area in western North Carolina (WNC), comprising 11440 km^2 and including parts of the southern Blue Ridge and Great Smoky Mountains (Fig. 1) to explore patterns of potential bioenergy crop productivity in a diverse landscape. Elevation ranges from 300 to 2040 m with steep topographic gradients leading to considerable variation in soil and climate conditions over short distances (Bolstad et al. 1998). Climate varies seasonally with warm, humid summers and cool winters. Annual mean precipitation is 1397 mm and occurs year round. Mean daily temperatures are 3.1°C, 11.7°C, 21.1°C, and 12.7°C for winter, spring, summer, and fall respectively. Soils are broadly classified as Ultisols or Inceptisols. At finer classification, over 1000 soil types, designated as map units by the USDA Soil Survey, are represented on current agricultural land in WNC (Soil Survey Staff 2013).

Land cover is dominated by forest (81%); agricultural lands make up ~10% of the land base and are typically located at low to mid-elevations (USDA CDL 2012). The remaining 9% of land cover is classified as developed, water, or barren. Agriculture, while occupying a smaller portion of the land base, generated nine times the 2011 annual cash receipts than all forest-based products combined in the WNC region (NCDAS 2013). Approximately 20% of the agricultural land in WNC is harvested cropland; the remaining agricultural land is primarily pasture or small woodlots (NCDAS 2013). Crop production represented 70% of farm cash receipts in the region in 2011; 40% of those receipts were generated from the sale of vegetables, fruits, nuts, and berries (NCDAS 2013).

Because of its scenic beauty, the region is popular for tourism and retirement living, with populations

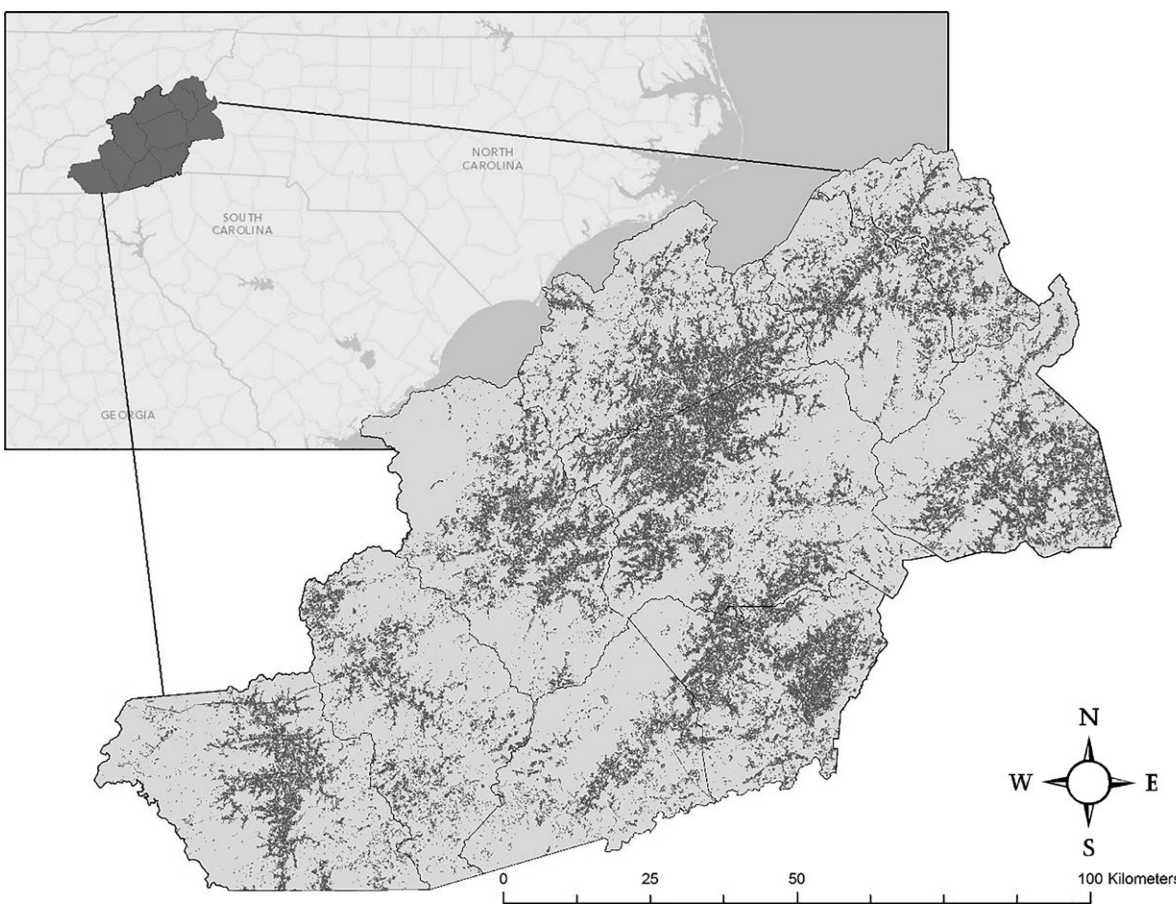

Fig. 1. Map of the 10-county region in western North Carolina, USA considered for bioenergy production. Shaded areas indicate current or fallow agricultural land.

increasing by 48% between 1976 and 2006 (Vogler et al. 2010). If current land conversion trends continue, projections suggest that an additional 5% of the land not currently protected will be converted to development by 2030 and human populations will increase by an additional 40% by 2050 (Vogler et al. 2010, GroWNC 2013). Stakeholders in the southern Appalachians are interested in identifying alternatives to exurban development that maintain the ecological and aesthetic character of these landscapes and sustain multiple ecosystem services (GroWNC 2013) and visitors to WNC express strong preferences for the scenic quality of farmland (Kask et al. 2002). In recent years, multiple farmland conservation initiatives have established in the region (Gragson et al. 2008).

Materials and Methods

Bioenergy crop yield in current and projected future climate

We simulated annual yield of three bioenergy crops using a process-based crop growth model, ALMANAC (Kiniry et al. 1992). ALMANAC has been parameterized for over 120 crops and used widely across multiple regions (Kiniry et al. 2005, see Kiniry et al. [1992], for full explanation of model inputs). We calibrated ALMANAC using mean biomass yields for switchgrass (a native warm-season grass), giant miscanthus (a non-native warm-season grass), and hybrid poplar (a hybridized fast-growing native tree) grown in Fletcher, North Carolina during 2008–2012 (Palmer et al. 2014, Stout et al. 2014). The default parameters for switchgrass "Southern lowland ecotype," giant miscanthus, and hybrid poplar were used, with a few modifications based on literature, expert knowledge, and calibration to observed data (J. Kiniry, *personal communication*; see Appendix S1: section S1). For all scenarios, management parameters assumed a planting date of 10 April during the first year of simulation and no irrigation. Fertilizer was applied as necessary to eliminate nitrogen limitation during model runs. For the two perennial grasses, simulations ran for 10 yr with annual harvest on 15 October. For poplar, simulations followed a 12-yr, short-rotation coppice cycle with harvesting occurring on 15 October in years 4, 8, and 12. Variation in local management will affect potential bioenergy crop productivity (McLaughlin and Adams Kszos 2005, Djomo et al. 2015), but we chose to hold management constant to isolate effects of climate change and environmental heterogeneity on bioenergy crop production. Sensitivity of ALMANAC to changes in climate, soil, and management parameters is well understood (Xie et al. 2003), but we performed a sensitivity analysis to understand its behavior in our landscape. Results of the sensitivity analysis revealed differences in crop growth responses between the grasses and hybrid poplar to changes in precipitation and soil texture and demonstrated that grass yields were more sensitive to changes in precipitation on finer-textured soils while hybrid poplar yields tended to increase with increasing precipitation, across all soil types (Appendix S1: section S2).

ALMANAC simulates field-scale crop production. We used existing gridded climate and soil data sets to delineate unique soil–climate combinations representing all possible field conditions across agricultural land in the study area. Daily surface weather and climatological summary (DayMet) data (1 km^2 grid cells) were overlaid with Soil Survey Geographic (SSURGO) data (map scale 1:20000) to generate a soil–climate layer, resulting in 69645 unique soil–climate combinations. We simulated bioenergy crop growth by running ALMANAC under current and future climate conditions for each of the three crops for each soil–climate combination. Soil parameters for all scenarios were assembled from the USGS SSURGO data set (Soil Survey Staff 2013).

Current climate scenario

Input parameters for the current climate scenario were obtained from existing data sources. ALMANAC contains a weather generator subroutine, which generates daily weather based on climate drivers (Kiniry et al. 1996). Daily climate drivers included monthly minimum and maximum temperature, mean monthly precipitation and the standard deviation of precipitation within each month, mean solar radiation, wind speed, and relative humidity were assembled from a 30-yr (1981–2001) DayMet data set (Thornton et al. 2012). The Daymet database is available at daily time steps at a 1-km resolution and was developed from data measured at a large number of weather stations. The monthly climate variables were mapped at a 1-km resolution to create a baseline climate surface and were used as input into the ALMANAC model to simulate bioenergy yields under current conditions.

Future climate scenarios

Future climate scenarios used downscaled daily climate drivers and carbon dioxide concentrations assembled from global circulation model (GCM) model-averaged climate projections from the CMIP-5 multi-model ensemble (Appendix S1: section S2) for the mid-century (2040–2050) and late century (2090–2100) under medium- and high-emissions scenarios: representative concentration pathway (RCP) 4.5 and RCP 8.5 (Maurer et al. 2007, Brekke et al. 2013). We created "future climate" scenarios by combining model-averaged global circulation model (GCM) climate predictions with the finer scale baseline climate data using the "delta method" (Hamlet et al. 2010). This approach is limited in that it assumes that relationships between variables in the baseline climate at high resolution are likely to be maintained under future conditions.

We downloaded data from a subset of the available CMIP-5 GCMs (see Appendix S1: Table S4 for complete list) corresponding to three time series: historical observed (1980–2000), mid-21st century (2040–2050), and late-21st century (2090–2100), at daily time steps, for three variables (minimum and maximum temperature, and precipitation) for RCPs 4.5 and 8.5. For each time period and each of GCM, we calculated the same nine monthly statistics as calculated for the baseline climate inputs (Appendix S1: Table S3). We averaged the monthly statistics across the GCMs to create a multimodel ensemble data set describing the mean monthly climate conditions for each time period. We calculated the anomaly (or delta) with respect to the mean observed climate (1980–2000) for each the variables and months. Anomaly values were used to create raster climate change surfaces for each of the nine variables at 1/8° latitude–longitude (~12 km) resolution. Finally, future climate surfaces were created by "adding" the anomalies to baseline climate surface for each variable and each month. For temperature, anomalies were added to observational baselines. Rainfall anomalies were added as absolute changes relative to the baselines (Ramirez-Villegas and Jarvis 2010). The resulting future climate surfaces (1-km resolution) were used as input into the ALMANAC model to simulate bioenergy yields under moderate (RCP 4.5) and extreme (RCP 8.5) climate change during to future time periods (2040–2050 and 2090–2100).

The magnitude of climate change depends on the emissions scenario with RCP 4.5 resulting in likely increases in global surface temperature of 1.1–2.6°C and RCP 8.5 leading to likely increases of 2.6–4.8°C by the end of the 21st century (IPCC 2014). Precipitation changes are not expected to be uniform, but precipitation is expected to increase under both RCP 4.5 and RCP 8.5. The southeastern United States is located in a transition zone between projected wetter and projected drier conditions, therefore future precipitation projections for the region are uncertain (Carter et al. 2014). Our model-average climate scenarios resulted in spatially varied precipitation, with some locations experience increases in precipitation and others experiencing decreases. ALMANAC uses the mean monthly precipitation, standard deviation of precipitation, as well as the probability and number of wet days per month to generate daily rainfall values allowing us to account for both spatial and temporal variation in projected precipitation (Kiniry et al. 1996).

Crop yield

We calculated mean annual yield (Mg·ha^{-1}·yr^{-1}) of each crop for each soil–climate combination. For statistical analysis, we randomly sampled 6000 soil–climate combinations (~10% of the entire data set) to reduce the likelihood of spurious results due to the high sample size of our simulated data (White et al. 2014). Differences among bioenergy crops under current climate were analyzed using repeated measures ANOVA with crop type as the main effect. Change in mean annual yield (relative to yield under current climate) under climate change scenarios was analyzed separately by crop type for the mid and late 21st century. Change in mean annual yield was analyzed using repeated measures ANOVA with climate scenario (RCP pathway) as the main effect.

Maximum landscape yield, crop allocation, and bioenergy hotspots

For each climate scenario, mean annual yield (Mg/yr) from bioenergy crop simulations was mapped back to the landscape using 1-ha grid cells. If a grid cell included more than one soil-climate combination, the mean of all the combinations was used. All scenarios were conducted on land currently in agricultural land use (defined as row crop, pasture, or fallow) or recently abandoned (USDA CDL 2012); the remainder of the landscape was considered unavailable for bioenergy crop production.

Maximum landscape yield and crop allocation.—To determine the maximum landscape yield, we assigned each cell to the bioenergy crop with the highest yield for each scenario. The proportion of the agricultural landscape assigned to each crop type to maximize landscape yield under each climate scenario was recorded. Maximum landscape yield (Mg/yr) for the resulting mixed-crop landscape was calculated by summing across grid cells. Individual crop yield (Mg/yr) for the resulting mixed-crop landscape is reported for each scenario. Differences in proportional crop allocation among current climate and future climate scenarios were assessed using chi-square test for significance.

Bioenergy hotspots.—Lands capable of producing high yields (>10 Mg·ha^{-1}·yr^{-1}, considered an economically viable level of production) and very high yields (>18 Mg·ha^{-1}·yr^{-1}, which represented the top 20% of the baseline yield distribution and we considered bioenergy hotspots), were identified for each climate scenario, and their total area (ha) and total yield (Mg/yr) were calculated by summing across these map cells.

Bioenergy hotspots and land-use competition

Food vs. fuel.—Potential conflict between food production (defined here as row crop or fruit tree production) and bioenergy production was determined by calculating the percent overlap of bioenergy hotspots with the distribution of current food crops. We then created a marginal-land-only scenario by removing land used for current food crop production from potential bioenergy production. Maximum landscape yield (Mg/yr), bioenergy hotspot area (ha) and total hotspot yield (Mg/yr) were calculated for the marginal-land-only scenario under each climate condition, and changes in these response variables were calculated to represent the potential bioenergy production "lost" to competition with food production in each climate scenario. We did not account for potential changes in the distribution of food production with climate change, assuming that the areas currently under cultivation represent the highest value agricultural land within the region.

Development vs. fuel.—Potential conflict between suburban/exurban development and bioenergy production was determined by calculating the percent overlap of bioenergy hotspots with areas having a high probability (>80%) of land use conversion to non-agricultural uses such as residential housing (Vogler et al. 2010). We removed these high-risk lands from potential bioenergy production, retaining all other agricultural lands. Maximum landscape yield (Mg/yr), bioenergy hotspot area (ha), and total hotspot yield (Mg/yr) were calculated for high-development scenarios under each climate condition. Percentage of change in maximum landscape yield, bioenergy hotspot area, and total bioenergy hotspot yield represent the bioenergy production "lost" to competition with development.

Results

ALMANAC estimated biomass productivity well for switchgrass, giant miscanthus, and hybrid poplar in the southern Appalachian Mountains (Table 1). The simulated 3-yr mean (2009–2012) was within 3% of harvest data for switchgrass and 2% for miscanthus. Harvest data were only available for 2 yr (2009 and 2012) for hybrid poplar; the difference between simulated and observed yields for those years was within 10%. These results suggest that ALMANAC is a satisfactory model for projecting biomass productivity potential in western North Carolina.

Bioenergy crop yield under current and future climate

Under current climate, mean annual yield of miscanthus, switchgrass, and hybrid poplar on agricultural land was high and varied among crops ($F_{2,5998}$ = 481.72, P < 0.0001), with simulated harvests of 15.8, 15.6, and 14.1 Mg·ha^{-1}·yr^{-1}, respectively (Table 2). Mean annual yield varied across soil–climate combinations (range: 0–28 Mg·ha^{-1}·yr^{-1}). Mean annual yield of all three crops increased for the period of 2040–2050 under the medium emissions scenario (RCP 4.5) but decreased under the very-high emissions scenario (RCP 8.5; Table 2). Mean annual yields for the period 2090–2100 varied among crops. Under the RCP 4.5 scenario, mean annual yield predicted for switchgrass changed little relative to current conditions (<0.5%), but mean annual yield of miscanthus decreased (−4%), and hybrid poplar yield increased (+ 8%; Table 2). The RCP 8.5 scenario led to further decreases in the mean annual yield of miscanthus (−39%) and switchgrass (−14%) and substantial increases in hybrid poplar mean annual yield (+21%).

Table 1. Simulated and observed yields (Mg·ha^{-1}·yr^{-1}) for 2009–2012 in Fletcher, North Carolina, USA.

Crop	Observed	Simulated	Difference
Switchgrass (*Panicum virgatum*)			
3-yr mean (2009–2012)	19.03	19.63	+3%
Miscanthus (*Miscanthus* × *giganteus*)			
3-yr mean (2009–2012)	18.3	17.97	−2%
Poplar (*Populus* × sp.)			
2009 harvest	9.4	8.5	−10%
2012 harvest	14.7	15.4	+5%

Note: Observed yields reported by Palmer et al. (2014) and Stout et al. (2014).

Table 2. Mean (CV) simulated yield of three bioenergy crops on agricultural land in western North Carolina under current and future climate scenarios resulting from medium representative concentration pathway (RCP; RCP4.5) and very-high (RCP8.5) emissions.

	Crop yield (Mg·ha^{-1}·yr^{-1})		
Climate	Miscanthus	Switchgrass	Poplar
Mean current climate (1981–2011)	15.82 (0.24)	15.56 (0.21)	14.12 (0.18)
2040–2050			
RCP 4.5	16.11 (0.24)	15.99 (0.24)	14.66 (0.22)
RCP 8.5	15.2 (0.26)	15.47 (0.28)	13.96 (0.34)
2090–2100			
RCP 4.5	15.15 (0.27)	15.59 (0.28)	15.22 (0.25)
RCP 8.5	9.65 (0.40)	13.32 (0.38)	17.12 (0.24)

Note: Mean and CV are the spatial mean and variation within the study area. Simulations were run on unique soil–climate combinations representing all possible field conditions.

Maximum landscape yield, crop allocation, and bioenergy hotspots

Maximum landscape yield and crop allocation.—Under current climate, maximum landscape yield of bioenergy on agricultural land in the study area was 1.5 million Mg/yr (Table 3). Under projected future climate, maximum landscape yield increased by 2.1% by 2050 but declined slightly (<1%) by 2100 under the RCP 4.5 scenario. Maximum landscape yield varied little (<1%) under RCP 8.5 by 2050. However, the RCP 8.5 scenario led to large decreases (−14% to −39%) in yield of grasses and large increases (20%) in poplar yield by 2100. Maximum landscape yield increased in the late-century by 90000 Mg/yr (6%) under the RCP 8.5 scenario, primarily due to increased poplar production.

The allocation of bioenergy crops required to maximize landscape yield in all future climate scenarios differed substantially from that in current climate (Fig. 2). Under current climate conditions, maximum yield crop required most of the agricultural landscape allocated to

Table 3. Maximum landscape yield of bioenergy crops on agricultural land in western North Carolina under current and future climate scenarios resulting from medium (RCP4.5) and very high (RCP8.5) emissions.

Climate	Maximum landscape yield (Mg/yr)	Individual crop yield (Mg/yr)		
		Miscanthus	Switchgrass	Poplar
Current climate	1552 519	1089 115	261 599	201 806
2040–2050				
RCP 4.5	1 585 169	588 442	599 557	364 519
RCP 8.5	1 563 495	339 361	544 972	668 285
2090–2100				
RCP 4.5	1549 758	375 830	564 616	612 073
RCP 8.5	1642 808	5631	93 269	1453 618

Note: Individual yield of each crop is reported for each scenario.

miscanthus (70%), followed by switchgrass (17%) and hybrid poplar (13%). Maximizing bioenergy production under both climate scenarios required allocating more land to switchgrass and poplar and less land to miscanthus by 2050. Land area allocated to miscanthus continued to decrease, reaching nearly zero under the RCP 8.5 scenarios, while the allocation of land to poplar increased to over 90% by 2100 (Fig. 2).

Bioenergy hotspots.—Under current climate, over 97% of the study area was predicted to have high annual yields (>10 $Mg \cdot ha^{-1} \cdot yr^{-1}$) of at least one bioenergy crop, and bioenergy hotspots (>18 $Mg \cdot ha^{-1} \cdot yr^{-1}$) occupied 22% of the study area (Fig. 3). Climate change scenarios led to increases in bioenergy hotspot area. By 2100, bioenergy hotspots occupied 29% and 61% of the study area under RCP 4.5 and RCP 8.5 scenarios, respectively (Fig. 4). Bioenergy hotspot yield increased in all climate change scenarios (Table 4). Under the RCP 4.5 scenarios, bioenergy hotspot yield was predicted to be highest in the mid-century (580 000 Mg/yr), while under the RCP 8.5 scenario the highest bioenergy hotspot yield (1 100 000 Mg/yr) was predicted at the end of the 21st century.

Bioenergy hotspots and land use competition

Food vs. fuel.—Across all climate scenarios, 28–30% of bioenergy hotspots were co-located with current row crop or fruit production. The area of overlap was largest in the late-century under RCP 8.5, due to large increases in bioenergy hotspot area (Table 4). Marginal-land-only scenarios led to 27% reductions of maximum landscape yield in all climate conditions. Bioenergy hotspot area (ha) and total bioenergy hotspot yield (Mg/yr) were reduced by 28–30% in each climate scenario, suggesting that the proportion of bioenergy production "lost" to competition with food production remains constant across all climate scenarios.

Development vs. fuel.—Overall 60% of the agricultural land in the study area, or 570 km^2, was at high risk of development (>80% probability of conversion). In all scenarios, bioenergy hotspots overlapped 46–53% with high development probability (Fig. 4). High development scenarios led to consistent declines of 37–39% in maximum landscape yield across all climate scenarios as compared to baseline development and current climate scenario (Table 4). In high-development scenarios, bioenergy hotspot yield (Mg/yr) declined by 32–38% under RCP 4.5 scenarios but increased under RCP 8.5 scenarios due to large increases in hybrid poplar productivity expanding the area of bioenergy hotspots by late 21st century (Table 4).

Discussion and conclusions

Our study identified spatial allocations of bioenergy crop types that could maximize bioenergy production in

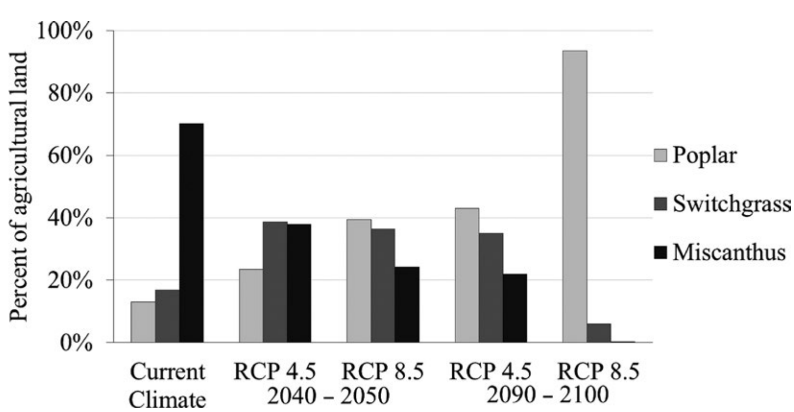

Fig. 2. Percentage of the agricultural landscape in western North Carolina potentially allocated to each bioenergy crop, based on simulated maximum yields under current climate (baseline) and future climate scenarios. Crops are switchgrass (*Panicum virgatum*), giant miscanthus (*Miscanthus* × *giganteus*), and hybrid poplar (*Populus* × sp.).

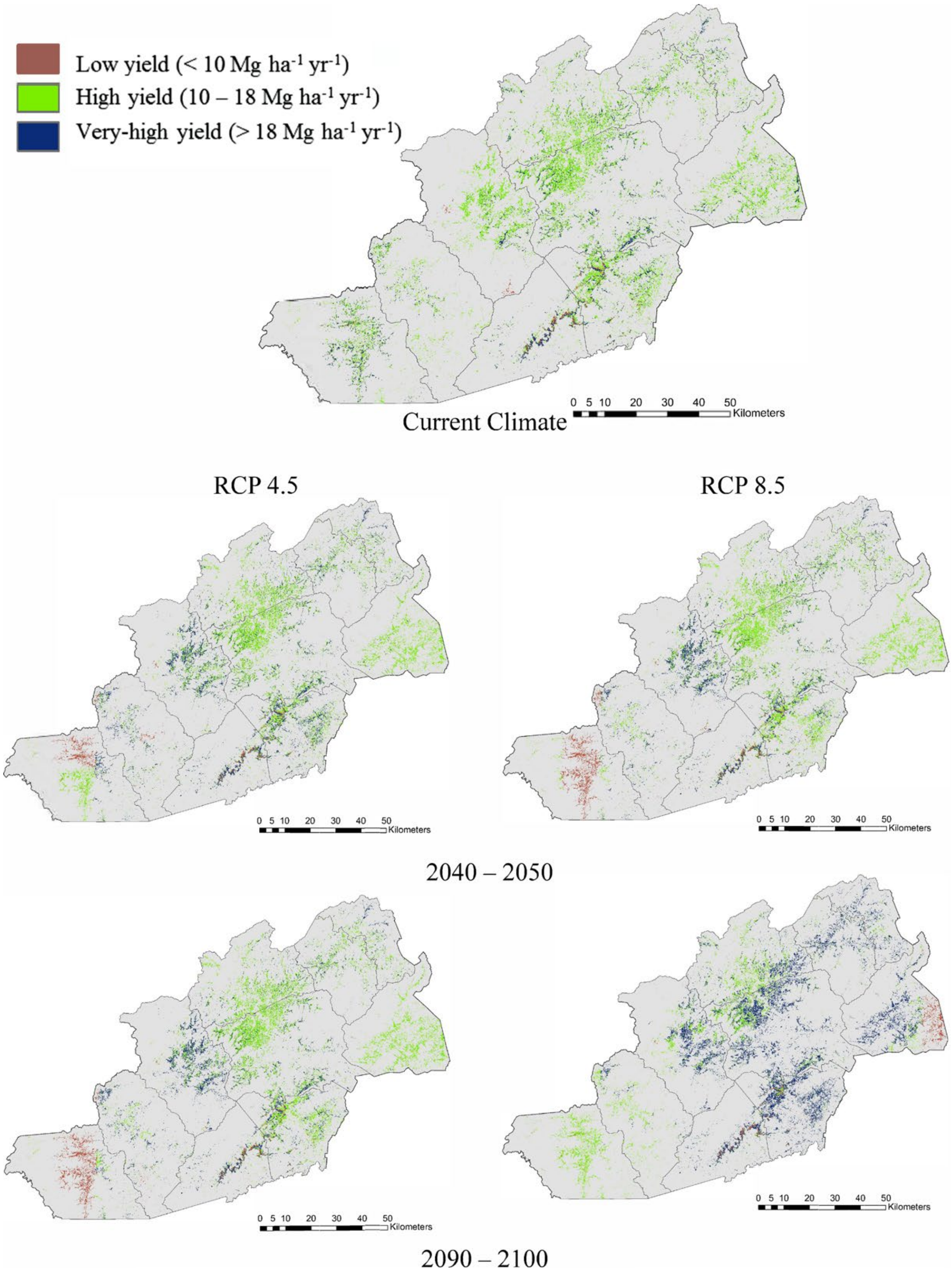

Fig. 3. Projected shifts in the distribution of bioenergy crop productivity on agricultural land in western North Carolina from current climate conditions to future climate scenarios resulting from medium representative concentration pathway (RCP; RCP4.5) and very high (RCP8.5) emissions during the mid- and late 21st century. Blue regions represent "bioenergy productivity hotspots" and produce > 18 $Mg \cdot ha^{-1} \cdot yr^{-1}$.

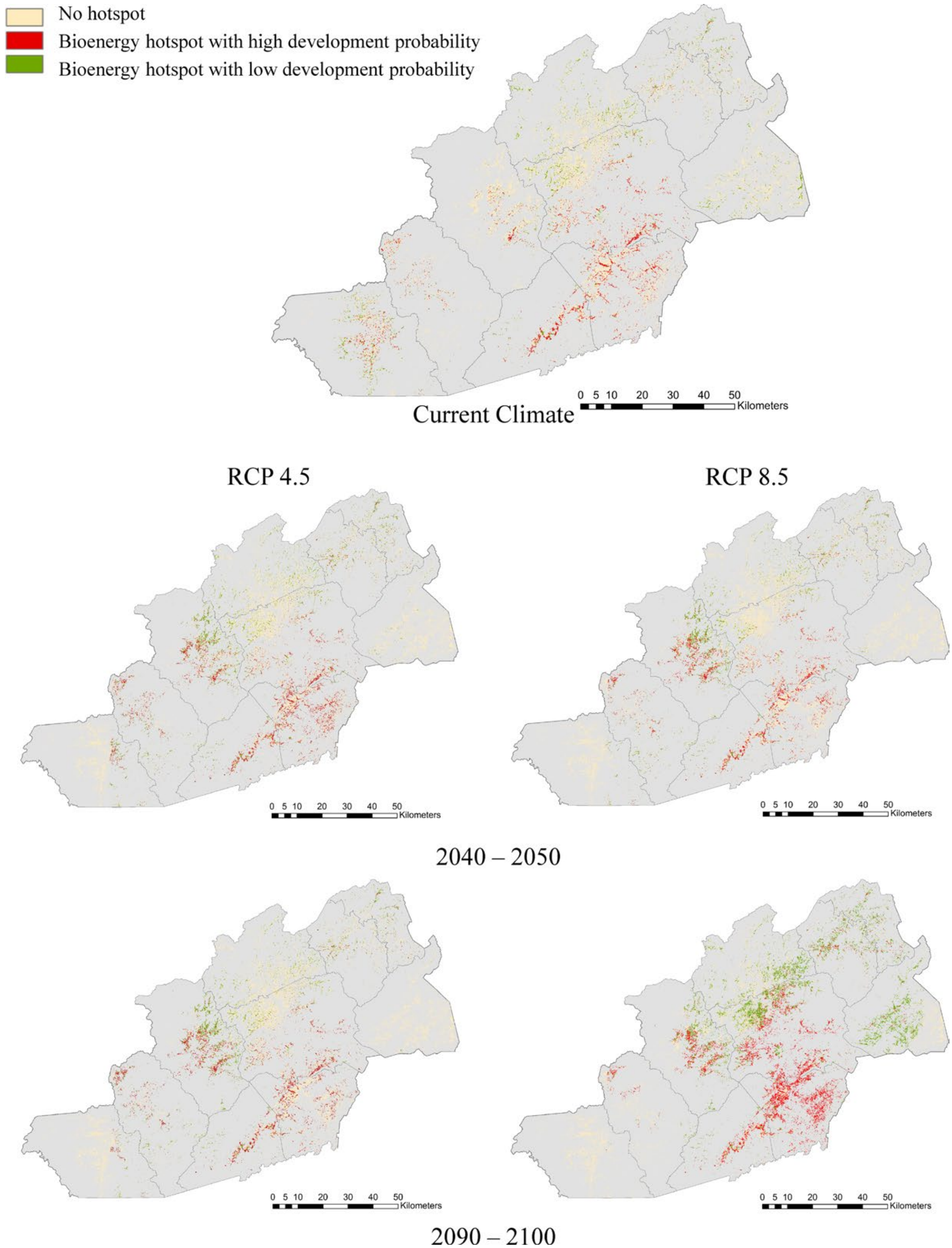

FIG. 4. Overlap of bioenergy productivity hotspots with high development probability under current climate conditions and future climate scenarios resulting from medium (RCP4.5) and very-high (RCP8.5) emissions scenarios.

TABLE 4. Bioenergy hotspot (>18 $Mg \cdot ha^{-1} \cdot yr^{-1}$ production) area and yield under multiple scenarios of climate and land-use competition on agricultural land in western North Carolina.

	Bioenergy hotspot percentage of landscape	Bioenergy hotspot yield (Mg/yr)	High-development scenario: bioenergy hotspot yield (Mg/yr)	Marginal-land scenario: bioenergy hotspot yield (Mg/yr)
Current climate (1981–2011)	22.1%	409 095		
2040–2050				
RCP 4.5	31.5%	589 735	279 342	414 572
RCP 8.5	26.8%	490 913	253 335	349 767
2090–2100				
RCP 4.5	28.8%	527 552	267 393	376 026
RCP 8.5	61.0%	1 095 182	590 112	787 056

the landscape as well as locations that are likely to be hotspots of bioenergy production under current and projected climate change. Using a mechanistic plant growth model to simulate bioenergy crop yield, we showed that giant miscanthus, switchgrass, and hybrid poplar have substantial yield potential in the complex landscapes of the southern Appalachians. Under climate change, maximum landscape yield of bioenergy increased by up to 90 000 Mg/yr in the 21st century. However, the type and extent of crops that maximize bioenergy yield will shift from grasses to woody species as climate warms during the 21st century, and tradeoffs among competing demands for multiple land uses (food, housing, and fuel) are likely. While the potential tradeoffs between bioenergy production, food production, and exurban expansion are not surprising, our study shows that the geographic locations of these tradeoffs vary substantially under changing climate. Further, there were striking differences in potential tradeoffs in the short- vs. long-term. Additionally, our study highlights the potential for bioenergy crops to mediate tradeoffs between development and the cultural heritage and landscape aesthetics that comprise the character of this region.

Bioenergy production has been suggested as a means for improving rural land tenure and mediating increased urbanization, particularly in conjunction with rural development programs (Dale et al. 2011*a,b*,). In our study, areas of high bioenergy production potential consistently overlapped with areas at high risk of conversion to development under both current and future climate scenarios. Thus, bioenergy crop production, in conjunction with active farmland protection programs and incentives, could provide a mechanism to maintain farmland in heterogeneous landscapes.

Projected climate change led to increases in estimated landscape-level yields due to increased growth of hybrid poplar. These results are consistent with studies showing increases in productivity of poplar and other C_3 species under CO_2 fertilization but limited increases or declines in productivity of C_4 plants (Liberloo et al. 2006). Our study evaluated changes in potential bioenergy crop productivity across steep biophysical gradients and in response to changed CO_2 levels, temperature and precipitation predicted under RCP 4.5 and RCP 8.5 scenarios. Long-term climate change may result in increased winter storms, flooding events, or drought in this region (Walsh et al. 2014) and further studies should address the vulnerability of crop productivity to these disturbance events. It is possible that new hybrids, developed to grow under changed climate conditions, could alter short- and long-term biomass production potential and provide options for farmers to adapt to weather-related disturbances (Ghimire and Craven 2011, Saibi et al. 2013).

Tradeoffs between provisioning services, such as the production of bioenergy, and regulating, cultural and supporting services, such as water quality, aesthetic views, and biodiversity, are common in the ecosystem services literature (Raudsepp-Hearne et al. 2010, Qiu and Turner 2013). A shift from grasses to woody crops to maximize bioenergy production would increase afforestation, leading to potential tradeoffs with other ecosystem services such as water availability (Perry et al. 2001), aesthetics, and species diversity (Li et al. 2014). Afforestation reduces overall streamflow and low flows in a watershed suggesting future tradeoffs between bioenergy production and water provisioning; however, afforestation can also lead to gains in water quality by reducing pollutant loads (van Dijk and Keenan 2007). Conversion of grassland or cropland to forest-based biomass can also lead to decreases in greenhouse gas emissions (Daystar et al. 2014). Afforestation would reduce grassland habitat in this forest-dominated landscape (Drummond and Loveland 2010), leading to possible declines in grassland nesting birds and other species reliant on open habitats (Brennan and Kuvlesky 2005). However, in landscapes such as the study area where natural land cover is forest, afforestation could more closely resemble prior conditions (Navarro and Pereira 2012) and bioenergy tree plantings could provide a low-contrast matrix and increase forest connectivity (Brockerhoff et al. 2008). Afforestation due to production of hybrid poplar would also lead to decreased landscape heterogeneity and change the aesthetics of the region, which has potential to affect stakeholders' perceptions of the landscape (Lindborg et al. 2009, Ruskule et al. 2013).

Bioenergy productivity hotspots were often co-located with areas currently in food production or at high risk of conversion to development, suggesting that competition with food production or exurban development may impact the future capacity to produce bioenergy in this landscape. Increasing development (e.g. high-development scenario) led to greater declines in bioenergy hotspot compared to eliminating competition with current food production (e.g. marginal land only). Across all climate scenarios, high bioenergy yields were possible on nearly half the agricultural land predicted to have high development pressure (>80% probability of conversion). Loss of agricultural land to development could greatly decrease the region's ability to produce bioenergy, suggesting that there are unrealized opportunity costs associated with landowners' decisions that should be incorporated into regional energy and agricultural planning, particularly with regard to human adaptation to climate change.

Our study suggests that high-yielding bioenergy crops offer farmers an additional commodity and an opportunity to offset agricultural land conservation costs. However, a number of environmental, economic, and sociopolitical constraints currently limit bioenergy crop production by farmers (Atwell et al. 2010, Skevas et al. 2014). The current lack of a strong market for perennial bioenergy crops and the uncertainties related to small landowners' market access, including the ability to transport crops across existing or improved infrastructure, will affect the opportunities for bioenergy crop production to contribute to farmland conservation in the United States. Our study, in accordance with others, suggests that farmers will be able to grow bioenergy crops on agricultural land not suitable for high-value food crops (Valentine et al. 2012, Werling et al. 2014). This additional income could tip the balance of economic forces in favor of keeping a farm in business and prevent conversion of farmland to more economically attractive land uses, like development (Dale et al. 2011*b*). Agricultural policies such as the availability of subsidies and incentives for growing bioenergy crops or setting aside land in return for compensation will influence the real potential for bioenergy production to supplant development in rural areas (Lovett et al. 2009, Barney and DiTomaso 2010, Bryngelsson and Lindgren 2013, Myhre and Barford 2013). Our results suggest that the bioenergy potential of marginal lands should not be ignored and bioenergy provides an additional alternative for farmers planning in the uncertainty of a changing climate (Dale et al. 2010).

Rural landscapes produce multiple goods and ecosystem services; this study highlighted potential tradeoffs among bioenergy production, crop production, and exurban expansion given projected climate change. Impacts of increased bioenergy production have been explored as part of "food, energy, environment trilemma" (Tilman et al. 2009). In rural landscapes at risk of exurban expansion, we suggest that bioenergy production may result in a win-win solution in the "trilemma" by avoiding potential environmental impacts of exurban development. Where bioenergy hotspots overlap with high risk of exurban development, bioenergy crop production may lead to benefits by increasing energy production while also conferring environmental benefits through land conservation. When compared to exurban encroachment on agricultural land, perennial bioenergy crops (e.g. warm-season grasses or fast-growing trees) enhance climate regulation, nutrient, and water cycling (Dale et al. 2014) and have either positive or neutral effects on biodiversity conservation (Immerzeel et al. 2014, Werling et al. 2014).

While bioenergy crop yields are projected to be high enough to provide opportunities to sustain rural farmlands facing competing demands on the land base, actual landscape change may take multiple pathways depending on individual farmers' land-use decisions. Individual decision making is complex and influenced by multiple factors such as personality, cultural context, and life events as well as perceived land suitability for a particular crop at the farm and regional scale (Atwell et al. 2010, Cope et al. 2011). Private land owner decisions and their future behaviors are key uncertainties in assessing future land use patterns and competition. Future research would benefit from considering heterogeneous behavior of decision makers (Pattanayak et al. 2004) and accounting for the fact that yield optimization is only one of many landowner goals (Sengupta et al. 2005, Greiner et al. 2009).

Our study estimates bioenergy crop generation potential and uses bioenergy crop yield to evaluate potential tradeoffs between bioenergy production, food production, and development. We evaluate tradeoffs with food production by analyzing the co-location of high bioenergy potential with current crop production. Considering that food crop yields will also be impacted by climate change (Challinor et al. 2009), future research should include projected yield and spatial variation of possible food crops under climate scenarios (Lehmann et al. 2013). In diverse agricultural landscapes with relatively small farms, farmers' crop choices are likely to be flexible and may be particularly adaptable to climate change (Howden et al. 2007, Veteto 2008, Crane et al. 2011). More research is needed to identify whether shifts in food crop production leads to greater or lesser tradeoffs with bioenergy crop production in heterogeneous landscapes.

Results from our study indicate that there is high potential for heterogeneous landscapes to produce bioenergy both currently and in changing climates, but spatial and temporal variation in potential yield will result in multiple, shifting landscape-level tradeoffs. Our findings illustrate the importance of incorporating realistic yield estimates, environmental heterogeneity, and socioeconomic forces in studies aimed at understanding the role of new crop production in future landscapes. Our study highlights regional and temporal contrasts in spatial patterns of bioenergy production and identifies important opportunities for bioenergy crop production to offset land conversion to development.

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