Regional Variations in Potential Plant Habitat Changes in Response to Multiple Global Warming Scenarios*

CHANG-EUI PARK

School of Earth and Environmental Sciences, Seoul National University, Seoul, South Korea

SU-JONG JEONG

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

CHANG-HOI HO

School of Earth and Environmental Sciences, Seoul National University, Seoul, South Korea

JINWON KIM

Department of Atmospheric Sciences, University of California, Los Angeles, Los Angeles, California

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ABSTRACT

This study examines the impacts of global warming on the timing of plant habitat changes in the twenty-first century using climate scenarios from multiple global climate models (GCMs). The plant habitat changes are predicted by driving the bioclimate rule in a dynamic global vegetation model using the climate projections from 16 coupled GCMs. The timing of plant habitat changes is estimated by the first occurrence of specified fractional changes (10%, 20%, and 30%). All future projections are categorized into three groups by the magnitude of the projected global-mean land surface temperature changes: low (<2.5 K), medium (2.5–3.5 K), and high (>3.5 K) warming. During the course of the twenty-first century, dominant plant habitat changes are projected in ecologically transitional (i.e., from tropical to temperate and temperate to boreal) regions. The timing of plant habitat changes varies substantially according to regions. In the low-warming group, habitat changes of 10% in southern Africa occur in 2028, earlier than in the Americas by more than 70 yr. Differences in the timing between regions increase with the increase in warming and fractional threshold. In the subtropics, fast plant habitat changes are projected for the Asia and Africa regions, where countries of relatively small gross domestic product (GDP) per capita are concentrated. Ecosystems in these regions will be more vulnerable to global warming, because countries of low economic power lack the capability to deal with the warming-induced habitat changes. Thus, it is important to establish international collaboration via which developed countries provide assistance to mitigate the impacts of global warming.

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Corresponding author address: Su-Jong Jeong, Jet Propulsion Laboratory, M/S 233-305D, 4800 Oak Grove Drive, Pasadena, CA 91109.
E-mail: Su-Jong.Jeong@jpl.nasa.gov

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1. Introduction

Changes in plant habitats are among the key responses of terrestrial ecosystems to climate change (Sturm et al. 2001; Rosenzweig et al. 2007; Xu et al. 2013). Recent observational studies show that the global warming induced by the emissions of anthropogenic greenhouse gases may have caused notable habitat changes, particularly for shrub- and grasslands in the high latitudes (Parmesan and Yohe 2003; Berner et al. 2005; Jia et al. 2009; Forbes et al. 2010). Future climate projection studies

also suggest that global warming may accelerate the current global habitat changes (Sala et al. 2005; Sitch et al. 2008; Gonzalez et al. 2010). The plant habitat changes can cause various ecological effects, such as decline in biodiversity, increased extinction risks, and alterations in biogeochemical cycles (Thomas et al. 2004; Bellard et al. 2012; Hartley et al. 2012), which can further alter local/regional climate through vegetation–climate feedback (Chapin et al. 2005; Bonan 2008; Jeong et al. 2011b; Park et al. 2012). Thus, understanding plant habitat changes due to global warming is crucial for mitigating and adapting to future climate and ecological changes.

Projections of ecosystem-level plant habitat changes in response to climate change have been made using dynamic global vegetation models (DGVMs) and bioclimate envelope models either driven by climate model forcing (Cramer et al. 2001; Sitch et al. 2008; Bellard et al. 2012) or coupled with global climate models (GCMs) (Bounoua et al. 2010; Jeong et al. 2011b). Plant habitat changes are investigated by contrasting the time–mean geographical distributions of plant habitats in a future period against that in a present-day period, in general [e.g., 2071–2100 minus 1961–90 in Scholze et al. (2006)]. This method is useful for measuring the amount of habitat change in targeted regions and periods (Lucht et al. 2006; Alo and Wang 2008) but is not suitable for obtaining the point of time (i.e., timing) at which a specified amount of habitat change will occur. The timing of plant habitat change can tell us which parts of the world will experience faster changes, indicating higher risks from habitat change. This also allows us to estimate the amount of time required for the occurrence of a specific amount of habitat change for a specific level of climate change. Information on the timing to exceed a particular threshold value is useful for the development and timely implementation of management plans to adapt to and mitigate the impact of plant habitat changes (Adger et al. 2007a; Joshi et al. 2011).

The primary objective of this study is to evaluate the regional variations in the timing of plant habitat changes corresponding to a specified level of global warming in terms of the surface air temperature. Forest management plans have been generally developed at regional or national levels (Adger et al. 2007b). Thus, regional variations in the timing of plant habitat changes are directly useful in forest management practices. We also examine the relationship between the gross domestic product (GDP) per capita and the projected timing of plant habitat changes to help individual nations in developing ecosystem management plans. Ecosystem management policy needs sufficient economic capability. Adaptation policies and actions cannot be implemented if the associated cost is too large for a nation to afford (Naidoo et al. 2006; Adger et al. 2007a; Chan et al. 2011). Nations with weaker economic capability

will experience difficulties in implementing mitigation plans and are thus more vulnerable to the same amount of habitat changes than wealthier nations.

To obtain future global plant habitat changes, this study projects the spatial and temporal variations in the changes of woody plant habitats in the twenty-first century using the bioclimate rule and multiple global warming scenarios from multiple atmosphere–ocean coupled GCMs. Because the bioclimate rule describes the plant habitat changes only in terms of the surface air temperature, the biotic factors such as the physiological impacts of CO₂ fertilization on plant habitat and competition among plant species under given climate change are not included in the projections. This may be an oversimplification in projecting plant habitat changes; however, a hierarchical framework in Turner et al. (2001) showed that climate is the highest environmental constraint for distribution of plant habitat in the global scale. This hierarchy of environmental variables is supported by limited impacts of the biotic factors when the climate change is less severe (Brown et al. 1998; Pearson and Dawson 2003). Thus, global plant habitat changes in response to climate change obtained using the bioclimate rule are reliable although they do not include the effects of other factors, such as CO₂ fertilization. This study has utilized all available climate model outputs from the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) archives to calculate the response of plant habitats to climate change (Meehl et al. 2007a). Ensembles of various projected habitat changes could cope with a wide range of inter-GCM variations in climate sensitivity (Meehl et al. 2007b).

2. Method

Habitat changes of woody plant species in response to global warming are assessed using the bioclimate rule of plant functional types (PFTs) in the Lund–Potsdam–Jena dynamic global vegetation model (LPJ-DGVM) (see Table 2 in Sitch et al. 2003), where the bioclimate rule for woody PFTs is defined by temperature-based bioclimatic limitation of survival and establishment. The climatic limitation is represented by range of the coldest-month temperature in the 20-yr running mean (T_c). For example, in regions where T_c ranges between 3° and 15.5°C, temperate needleleaf evergreen, temperate broadleaf evergreen, temperate broadleaf summergreen, and temperate herbaceous plants can coexist. The bioclimate rule has been used in a number of previous studies on future vegetation changes using LPJ-DGVM-based models (Lucht et al. 2006; Alo and Wang 2008; Scholze et al. 2006; Jiang et al. 2012). On the basis of the bioclimate rule, eight plant habitats are defined according to dominant PFTs (Table 1): tropical

TABLE 1. Bioclimate limits for plant habitats: $T_{c,\min}$ is the minimum coldest-month temperature for survival; $T_{c,\max}$ is the maximum coldest-month temperature for survival.

Plant habitat			$T_{c,\min}$ (°C)	$T_{c,\max}$ (°C)
Tropical PFTs-dominated habitat (Tr-type)	Tr1	Tropical broadleaf green	22	—
		Tropical herbaceous		
	Tr2	Tropical broadleaf green	18.8	22
		Temperate needleleaf evergreen		
Temperate PFTs-dominated habitat (Te-type)	Te1	Tropical herbaceous		
		Tropical broadleaf green	15.5	18.8
		Temperate needleleaf evergreen		
		Temperate broadleaf evergreen		
	Te2	Tropical herbaceous		
		Temperate needleleaf evergreen	3	15.5
		Temperate broadleaf evergreen		
		Temperate broadleaf summergreen		
	Te3	Temperate herbaceous		
		Temperate needleleaf evergreen	−2	3
		Temperate broadleaf summergreen		
	Te4	Temperate herbaceous		
		Temperate broadleaf summergreen	−17	−2
		Boreal summergreen		
		Boreal needleleaf evergreen		
	Boreal PFTs-dominated habitat (Bo-type)	Bo1	Temperate herbaceous	
Boreal summergreen			−32.5	−17
Boreal needleleaf evergreen				
Bo2		Temperate herbaceous		
		Temperate herbaceous	—	−32.5

(Tr-type: Tr1 and Tr2), temperate (Te-type: Te1, Te2, Te3, and Te4), and boreal (Bo-type: Bo1 and Bo2). For every year in the analysis period, the spatial distribution of T_c is transformed into the spatial distribution of plant habitats following the T_c ranges in Table 1. Thus, the distribution of plant habitats is calculated at annual time steps with the horizontal resolution same as T_c . To remove remaining nonvegetative regions (i.e., deserts), the tropical and temperate regions with annual precipitation totals <200 mm (Ezcurra 2009; Jeong et al. 2011a) are excluded. Polar deserts in the arctic region are defined as the areas of annual precipitation totals <250 mm with the warmest-month temperatures <10°C (Ezcurra 2009). In addition, the land-cover product from the Moderate Resolution Imaging Spectroradiometer retrievals is used to verify the present-day distributions of the eight plant habitats and deserts (Friedl et al. 2002).

Surface temperature and precipitation data for identifying plant habitats are obtained from long-term integrations of 16 fully coupled GCMs in the third phase of the Coupled Model Intercomparison Project (CMIP3; Meehl et al. 2007a). All GCM outputs are first statistically downscaled onto a $0.5^\circ \times 0.5^\circ$ latitude–longitude grid for the period 1950–99 using the bias-corrected spatial downscaling (BCSD) scheme of Wood et al. (2004) in conjunction with the gridded observations of Adam and Lettenmaier (2003). We have analyzed a total of 48 sets of downscaled GCM simulations: 48

present-day simulations following the Special Report on Emissions Scenarios (SRES) 20C3M for 1950–99 and a subsequent 48 (16×3) future projections corresponding to the SRES B1, A1b, and A2 emissions scenarios for 2000–99. The 20C3M simulations are evaluated against the Climate Research Unit Time Series v3.0 (CRU TS3.0) of land surface temperature and precipitation analysis on a $0.5^\circ \times 0.5^\circ$ grid over the global land surface (Harris et al. 2014). The 20-yr running averages of the land surface temperature and precipitation are used as inputs for the bioclimate rule to compute the spatial distribution of the plant habitat for the period of 1970–2099.

We use the global-mean warming thresholds for all emissions scenarios to calculate habitat changes corresponding to specified amounts of global-mean land surface temperature changes. The global-mean surface temperature is conventionally used to represent the degree of climate change (Scholze et al. 2006; Solomon et al. 2007), because different degrees of global-mean temperatures are reflected by the combined impacts of land-use and greenhouse gas changes (Joshi et al. 2011). In addition, the global-mean temperature change is relevant to planning mitigation policies about the impact of climate change (Meinshausen et al. 2009; UNFCCC 2009). Thus, assessing the climate change impact as a function of the global-mean temperature change is a rational way to quantify the climate change impacts (Scholze et al. 2006; Joshi et al. 2011). The 48 sets of GCM

TABLE 2. The gross domestic product (GDP) per capita of nations for which all or some part of its territory is included in each region (The World Bank 2013).

Latitudinal belt	Region	Nation	GDP per capita [US dollars (USD)]
10°–25°S	Southern Africa	Angola	5688
		Botswana	7317
		Namibia	5462
		Madagascar	471
		Mozambique	593
		Zambia	1540
		Zimbabwe	905
	Central South America	Bolivia	2868
		Brazil	11 208
		Paraguay	4403
15°–30°N	East Asia	Bangladesh	829
		Bhutan	2498
		China	6807
		India	1499
		Lao PDR	1646
		Nepal	694
		Pakistan	1299
		Philippine	2765
		Thailand	5779
		Vietnam	1911
	Southern North America	Mexico	10 307
		Cuba	—
		United States	53 143
	Northern Eurasia	Kazakhstan	13 172
		Russia	14 612
	Northern North America	Canada	51 958
		United States	53 143

projections are grouped into three categories following the projected global-mean land surface temperature differences (ΔT) between the late twenty-first century period (2080–99) and the present-day period (1980–99): $\Delta T < 2.5$ K as low warming, 2.5 K $< \Delta T < 3.5$ K as medium warming, and $\Delta T > 3.5$ K as high warming. These warming thresholds are larger than in Scholze et al. (2006) by 0.5 K because the warming signal is generally larger over lands than ocean surfaces (Meehl et al. 2007b). Using these threshold values, 12, 18, and 18 sets of GCM projections are categorized into the low-, medium-, and high-warming groups, respectively (supplementary Table 1). For all warming thresholds, the timing at which a plant habitat changes by 10%, 20%, and 30% is estimated. In a specific analysis domain, the fractional change is computed by a ratio of the area where plant habitat change occurs to the total area in that region. A year at which the ratio first exceeds 10%, 20%, or 30% indicates the timing of 10%, 20%, or 30% habitat change, respectively. The timing is computed based not only on the ensemble mean, but on 10% and 90% of model projections to deal with the uncertainty in model simulations. Because previous studies showed that the regional mean fraction of wood species is likely to be $< 20\%$ over the globe, these three habitat-change thresholds

must be sufficiently large to capture meaningful habitat changes (Scholze et al. 2006; Sitch et al. 2008).

The GDP per capita means GDP for the total economic size of each nation divided by midyear population (The World Bank 2013). This economic index is adopted to evaluate the relationship between the timing of plant habitat change and regional economic power. Table 2 shows the 2013 GDP per capita values of all nations that have some or all of their territory located within the latitude bands 10°–25°S, 15°–30°N, and 50°–65°N (The World Bank 2013). Notice that these three latitude bands are found to have significant plant habitat changes, as shown in later sections. The six selected nations (Botswana, Brazil, China, Mexico, Russia, and Canada) have the largest GDP per capita values in each region, representing the upper limits of regional economic power. The United States is excluded from the representative nations because only a small part of it is located within the latitudes 15°–30°N and 50°–65°N.

3. Results

Figure 1 shows that the 20C3M runs reasonably simulate the present-day (1980–99) climatology of temperature and precipitation depicted by CRU with the

Present day (1980–1999) climatology

FIG. 1. Spatial distributions of averaged temperature of (a) CRU and (b) the ensemble of 20C3M simulations; and precipitation of (c) CRU and (d) the ensemble of 203CM simulations for present day (1980–2009).

Pearson correlation coefficients of spatial patterns of 0.99 and 0.95 for the temperature and precipitation, respectively. The differences in the global means are also small: 0.44°C for temperature and $-1.83\text{ mm month}^{-1}$ for precipitation, respectively (Table 3). Also the regional mean of the simulated temperature and precipitation is similar to CRU for each continent (Table 3). Figure 2 shows the temperature and precipitation changes for the low-, medium-, and high-warming groups in the period 2080–99. For all these groups, surface temperature increases for all land surfaces (Figs. 2a,b,c) with global-mean changes of 2.10° , 3.01° , and 4.10°C in the low-, medium-, and high-warming groups, respectively (Table 4). For each continent, the increase in surface temperatures is proportional to the amount of global warming (Table 4). Precipitation changes are generally positive, but precipitation changes are small or negative for the central Asia, Mediterranean, southern Africa, and central America regions (Figs. 2d,e,f). The global-mean precipitation increases by 3.45 , 4.76 , and $4.35\text{ mm month}^{-1}$ in the low-, medium-, and high-warming groups, respectively (Table 4). In contrast to the temperature change, the continental change in precipitation is largest in the medium-warming group, except for North America and Asia (Table 4) because of large decreases in precipitation on South America, southern Africa, and the Mediterranean in the high-warming group (Fig. 2f).

Figure 3 shows the spatial distributions of the eight plant habitats and desert areas in the present-day climate based on the CRU data and 20C3M GCM simulations. The habitat distributions in the late twenty-first century calculated for the low-, medium-, and high-warming groups are also shown. For the present-day period, the global distribution of plant habitats from the SRES 20C3M simulations is similar to those based on CRU (Fig. 3a versus Fig. 3b). Plant habitats calculated using the CRU and GCM temperatures vary with latitudes in general. The temperate habitats are bounded by the boreal habitats around 55°N , and most of the tropical habitats are located between 20°S and 20°N . In the eastern regions of

TABLE 3. Annual mean temperature and precipitation ($\pm$ std dev) of CRU and 20C3M simulations for present day.

Continent	Temperature ($^{\circ}\text{C}$)		Precipitation (mm month^{-1})	
	CRU	20C3M	CRU	20C3M
Globe	13.45	13.01 (± 0.09)	68.89	70.72 (± 1.26)
Africa	23.54	23.30 (± 0.06)	48.72	56.59 (± 1.05)
Asia	9.15	8.37 (± 0.11)	53.19	52.71 (± 1.05)
Australia	21.96	21.69 (± 0.07)	44.72	40.63 (± 1.25)
Europe	10.60	10.09 (± 0.10)	52.60	55.84 (± 1.01)
North America	6.01	5.23 (± 0.12)	62.76	65.30 (± 1.20)
South America	21.80	21.81 (± 0.06)	128.69	137.10 (± 2.03)

FIG. 2. Spatial distribution of changes in averaged temperature (2080–99 minus 1980–99) for (a) 12 models in the low-, (b) 18 models in the medium-, and (c) 18 models in the high-warming threshold. Changes in averaged precipitation for (d) low-, (e) medium-, and (f) high-warming thresholds.

northern Eurasia and North America, plant habitat boundaries appear at lower latitudes than in the western part of these continents. This spatial pattern of plant habitat in the present day resembles satellite-retrieved biome distributions (supplementary Table 2 and supplementary Fig. 1).

The projected plant habitats in the late twenty-first century show notable differences from the present-day distribution, even in the low-warming group ($\Delta T < 2.5$ K) (Fig. 3c). In the low-warming group ($\Delta T < 2.5$ K), two prominent features characterize plant habitat changes. First, tropical habitats expand substantially

TABLE 4. Projected changes in annual mean temperature and precipitation ($\pm$ std dev) for low-, medium-, and high-warming groups in future (2080–99).

Continent	Temperature			Precipitation		
	Low	Medium	High	Low	Medium	High
Globe	2.10 (± 0.48)	3.01 (± 0.50)	4.10 (± 0.57)	3.45 (± 5.15)	4.76 (± 7.17)	4.34 (± 8.91)
Africa	2.02 (± 0.43)	2.87 (± 0.45)	3.82 (± 0.45)	1.20 (± 4.51)	1.64 (± 5.91)	1.04 (± 7.19)
Asia	2.25 (± 0.52)	3.26 (± 0.53)	4.47 (± 0.59)	3.82 (± 3.76)	5.45 (± 4.97)	6.36 (± 6.20)
Australia	1.85 (± 0.31)	2.58 (± 0.43)	3.31 (± 0.45)	1.48 (± 4.26)	2.31 (± 4.74)	2.02 (± 7.37)
Europe	2.06 (± 0.44)	3.05 (± 0.54)	4.00 (± 0.60)	1.04 (± 3.56)	0.77 (± 4.58)	−0.97 (± 4.29)
North America	2.26 (± 0.50)	3.19 (± 0.55)	4.39 (± 0.66)	4.25 (± 4.77)	5.18 (± 6.06)	5.51 (± 7.56)
South America	1.77 (± 0.41)	2.55 (± 0.42)	3.58 (± 0.55)	4.27 (± 9.70)	6.08 (± 16.20)	1.19 (± 20.19)

Distribution of plant habitat

FIG. 3. Spatial distribution of averaged plant habitat of present day (1980–99) for (a) CRU and (b) the ensemble of 20C3M simulations. Spatial distribution of averaged plant habitat of future projection (2080–99) for (c) 12 models in the low-, (d) 18 models in the medium-, and (e) 18 models in the high-warming thresholds. Regions with gray shading represent the desert areas.

into adjacent temperate habitats, mainly in central South America, southern Africa, northern Australia, and India. The area of tropical habitats is projected to increase by 15.4% from the present day as a result of the increase in the Tr1-type habitat (tropical broadleaf green and tropical herbaceous) by up to $5.39 \times 10^6 \text{ km}^2$, about 22% of the present-day area (Table 5). Expansion of the tropical habitats is accompanied by the contraction of the two habitat types Te1 (tropical broadleaf

green, temperate needleleaf evergreen, temperate broadleaf evergreen, and tropical herbaceous) and Te2 (temperate needleleaf evergreen, temperate broadleaf evergreen, temperate broadleaf summergreen, and temperate herbaceous), suggesting the decrease in the temperate woody species in temperate regions. The boreal habitats decrease in the northern regions of Eurasia and North America by $3.6 \times 10^6 \text{ km}^2$, 15.1% of the present-day value (Table 5). The decrease in the

TABLE 5. Area of observed and projected plant habitat (10^6 km^2). The numbers are the total area (in 10^6 km^2) covered by each climate type. The numbers in parentheses are one std dev of total area (in 10^6 km^2) projected by 12, 18, and 18 projections in low-, medium-, and high-warming groups.

Years	Data	Tr1	Tr2	Te1	Te2	Te3	Te4	Bo1	Bo2
1980–99	Obs (CRU)	25.27	8.55	8.05	19.94	6.60	19.81	21.48	3.65
	All	24.66 (0.26)	9.07 (0.15)	8.36 (0.09)	20.17 (0.38)	6.62 (0.18)	19.30 (0.40)	18.84 (0.39)	4.95 (0.26)
	Low	24.72 (0.17)	9.02 (0.09)	8.32 (0.05)	20.15 (0.27)	6.66 (0.14)	19.22 (0.23)	18.85 (0.29)	4.99 (0.22)
	Medium	24.68 (0.19)	9.06 (0.11)	8.35 (0.05)	20.14 (0.23)	6.61 (0.09)	19.29 (0.25)	18.89 (0.23)	4.95 (0.18)
	High	24.62 (0.19)	9.10 (0.11)	8.38 (0.04)	20.16 (0.24)	6.61 (0.10)	19.34 (0.26)	18.84 (0.17)	4.91 (0.15)
2080–99	Low	30.66 (1.03)	8.28 (0.29)	6.95 (0.67)	18.73 (0.78)	7.53 (0.41)	21.55 (1.12)	17.20 (0.72)	2.99 (0.75)
	Medium	32.57 (0.96)	8.32 (0.30)	6.16 (0.55)	18.33 (0.79)	7.81 (0.58)	22.24 (1.32)	16.05 (0.97)	2.34 (0.50)
	High	34.76 (0.97)	7.98 (0.35)	5.27 (0.75)	17.80 (0.97)	7.95 (0.63)	23.18 (0.99)	14.39 (0.82)	1.68 (0.37)

boreal habitat is accompanied by northward propagation of the Te3- (temperate needleleaf evergreen, temperate broadleaf summergreen, and temperate herbaceous) and Te4-type (temperate broadleaf summergreen, boreal summergreen, boreal needleleaf evergreen, and temperate herbaceous) habitats by $0.87 \times 10^6 \text{ km}^2$ and $2.33 \times 10^6 \text{ km}^2$, 13.7% and 11.7% of the present-day values, respectively (Table 5).

These habitat changes are further enhanced in the medium- and high-warming groups, $2.5 \text{ K} < \Delta T < 3.5 \text{ K}$ and $3.5 \text{ K} < \Delta T$, respectively (Figs. 3d,e). The warming magnitude is monotonically related with the increase in the tropical habitats and with the decrease in the boreal habitats. Compared to the low-warming group, the tropical habitats increase further by $1.95 \times 10^6 \text{ km}^2$ and $3.80 \times 10^6 \text{ km}^2$ in the medium- and high-warming groups, respectively (Table 5). Similarly, the boreal habitats decrease further by $1.80 \times 10^6 \text{ km}^2$ and $4.12 \times 10^6 \text{ km}^2$ in the medium- and high-warming groups, respectively (Table 5). These changes indicate that the tropical habitats will increase as much as the decrease in the boreal habitats for the high-warming group. However, the proportions of the area changes to the present-day area are up to 5.8% and 11.3% for the tropical habitats and 7.6% and 17.3% for the boreal habitats in the medium- and high-warming groups, respectively. These changes suggest that the risk of changes to boreal habitats will be larger than that to tropical habitats because of larger warming.

The projected spatial patterns of plant habitats in the late twenty-first century show that most habitat changes are observed in the boundary regions between the tropical (temperate) and temperate (boreal) plant habitats. This is evident in the zonal-mean patterns of the fractional change in plant habitats. Figure 4 shows the zonal mean of the fractional changes in the tropical, temperate, and boreal habitats for the low-, medium-, and high-warming groups in the late twenty-first century. Generally, the fractional changes are most noticeable in three zonal belts: $10^\circ\text{--}25^\circ\text{S}$, $15^\circ\text{--}30^\circ\text{N}$, and $50^\circ\text{--}65^\circ\text{N}$ (see the regions between dotted lines in Fig. 4). Fractional changes also increase with the warming strength. The variation in the fractional change according to the magnitude of warming is largest in the latitudinal band $10^\circ\text{--}25^\circ\text{S}$, where the projected maximum increase in the tropical habitats is as large as 20% (Fig. 4a). Around 20°S , the increase in the tropical habitats is as large as 60% in the high-warming group, while the low-warming group shows just 20% of change in the tropical habitats at the same latitude. In the regions $15^\circ\text{--}30^\circ\text{N}$ and $50^\circ\text{--}65^\circ\text{N}$, the fractional changes in the temperate and boreal habitats also increase with warming amplitudes (Figs. 4b,c). The largest difference

in the fractional change between the high- and low-warming groups is 40% at 25°N and 20% at 55°N . Consequently, overall patterns show that the decrease (or increase) in the boreal (or tropical) plant habitat fractions is accompanied by the increase (or decrease) in the temperate plant habitat fractions.

Based on the changes in the plant habitat for the three latitude bands, we further estimate the timing of the plant habitat change related to the three warming groups. Figure 5 plots the percentage of plant habitat change from the present day (abscissa) against time (ordinate) for the three latitude bands. As the plant habitat changes induced by various climate model forcings vary widely, we focus on the ensemble mean of the projected plant habitat changes in the three groups (solid lines). In the region $10^\circ\text{--}25^\circ\text{S}$, the ensemble mean exceeds 10% in 2034 for the high-warming group (Fig. 5a and Table 6). This timing of the amount of the habitat change precedes that of the low- and medium-warming groups by 13 and 6 yr, respectively (Fig. 5a and Table 6). Increasing the threshold of the fractional change to 20% and 30% also increases the difference in the timing between the high- and other warming groups. The timing gap is 37 yr between the low- and high-warming groups at 20% threshold, and 11 and 20 yr between the medium- and high-warming groups at 20% and 30% threshold, respectively. In the region $15^\circ\text{--}30^\circ\text{N}$, the mean habitat changes reach 10% and 20% in the years 2045 and 2075, respectively, in the high-warming group (Fig. 5b and Table 6), earlier than those in the low-warming group by 11 yr at the 10% threshold, and those of the medium-warming group by 5 and 20 yr at the 10% and 20% thresholds, respectively. In the latitudes $50^\circ\text{--}65^\circ\text{N}$, the plant habitat change also occurs earlier, as the warming magnitude increases at all thresholds of fractional change (Fig. 5c and Table 6). Overall patterns of the projected plant habitat changes suggest that increased warming leads to faster habitat changes.

Because of the spatial heterogeneity of plant habitat changes, regional discrepancies in the timing of the mean plant habitat changes are analyzed for the three latitudinal belts in each continent (Table 6). The most dominant features are found between southern Africa ($0^\circ\text{--}60^\circ\text{E}$) and central South America ($30^\circ\text{--}90^\circ\text{W}$) in the latitudes $10^\circ\text{--}25^\circ\text{S}$. In the medium-warming group, for example, the 10% habitat change occurs in 2026 for the southern Africa region but in 2070 for the central South America region. This time difference in achieving the same amount of habitat change between these two regions indicates that southern Africa will experience larger and faster habitat change under the same global warming. This regional variation is intensified as the warming increases. In southern Africa, the timing of plant

FIG. 4. Difference of zonal-mean fractional change in plant habitat between the period of 2080–99 and 1980–99 for (a) tropical habitat, (b) temperate habitat, and (c) boreal habitat. Red dashed, green solid, and blue dotted lines indicate high-, medium-, and low-warming thresholds.

habitat change at 30% threshold is advanced by 37 yr when the level of global warming increases from low- to high-warming groups. However, central South America shows no change in the timing for achieving the 30% change for all three warming groups. Similar regional variations in the timing occur in the regions 15°–30°N between East Asia (60°–150°E) and southern North America (60°–120°W) (Table 6); the same amount of plant habitat change occurs earlier in East Asia than in southern North America. The regional variation is also amplified with increasing warming magnitudes.

For the region between 50°–65°N, the difference between northern Eurasia (30°E–180°) and northern North America (50°–170°W) is relatively small

compared to other latitude bands (Table 6). The warming magnitude has only small impacts on the regional difference in the timing of the plant habitat change. Instead, the threshold value for the fractional habitat change is more important in examining the regional variations in the temporal changes in plant habitat. For the 10% threshold, difference in the timing of plant habitat change is not significant between northern Eurasia and northern North America, whereas the timing is faster in northern North America than in northern Eurasia at the 20% and 30% threshold (Table 6). In the high-warming group, the difference in the timing is one year between northern Eurasia and northern North America for the 10% threshold, whereas

FIG. 5. Regional mean fractional changes in plant habitats for (a) 10° – 25° S, (b) 15° – 30° N, and (c) 50° – 65° N. Each projection from the CMIP3 model simulation included in low- (light blue), medium- (light green), and high-warming groups (light orange) are. Bars represent the range of timing when projected habitat changes might cross the 10%, 20%, and 30% thresholds of low- (blue), medium- (green), and high-warming (red) groups.

the timing appears earlier in northern North America for the 30% threshold (Table 6).

Considering significant variations in climate projections between GCMs, the multimodel ensemble mean of the timing of the plant habitat changes is analyzed. The

use of a multimodel ensemble mean tends to outperform individual models (e.g., Gleckler et al. 2008), although the uncertainty in climate projections still exists. In Fig. 5, color bars show the range of the projected timing of plant habitat change. The upper and lower limits of

TABLE 6. Estimated year during which the ensemble mean of projected habitat changes first exceeds the 10%, 20%, and 30% threshold for all warming groups in the three latitude belts. An em dash means that the ensemble mean does not reach the threshold before 2099.

	Low warming ($\Delta T < 2.5$ K)			Medium warming (2.5 K $< \Delta T < 3.5$ K)			High warming ($\Delta T > 3.5$ K)		
	10%	20%	30%	10%	20%	30%	10%	20%	30%
10°–25°S	2047	2094	—	2040	2068	2096	2034	2057	2076
Southern Africa	2028	2063	2094	2026	2053	2067	2020	2044	2057
Central South America	—	—	—	2070	—	—	2059	—	—
15°–30°N	2056	—	—	2050	2095	—	2045	2075	—
East Asia	2056	—	—	2052	2089	—	2046	2071	—
Southern North America	—	—	—	2077	—	—	2065	—	—
50°–65°N	2056	—	—	2049	2085	—	2045	2069	2097
Northern Eurasia	2047	—	—	2041	2086	—	2040	2070	—
Northern North America	2050	2084	—	2047	2073	2093	2039	2060	2073

the timings are provided as exact year on top and bottom of each colored bar, respectively. If the timing for the upper limit exceeds 2099, it is indicated by an arrow pointing upward. Larger ranges with wider spreads of projections indicate that the uncertainty in the timing represented by the ensemble mean is large. The ranges of projected timings in the low-warming group are larger than those in the medium- and high-warming groups for the 10% thresholds (Fig. 5). In the region of 10°–25°N, for example, the range of projected timing is 46, 37, and 31 yr for the low-, medium-, and high-warming groups for the 10% threshold. The range also varies for different latitudinal zones. The latitudes of 50°–65°N show broader range than other latitudes, especially at the 10%

threshold of the fractional change (Fig. 5). The wide ranges of the regions of 50°–65°N are closely related to large uncertainties in temperature projections in the high latitudes (Meehl et al. 2007b).

Because of the large variations in the projected timing, the relationship between the warming magnitude and the timing of plant habitat change is revised by changing the standard from the ensemble mean to the 90% proportion among all models (Table 7). Analyses based on the timing of the 90% proportion can increase the confidence level, because the 90% proportion indicates that particular habitat changes are almost certain to occur at a certain time. The timing of the 90% proportion is later than that of the ensemble mean by

TABLE 7. Estimated year during which 10% and 90% of model simulations of projected habitat changes first exceed the 10%, 20%, and 30% thresholds for all warming groups in the three latitude belts. An em dash means that the ensemble means does not reach the threshold before 2099.

		Low warming ($\Delta T < 2.5$ K)			Medium warming (2.5 K $< \Delta T < 3.5$ K)			High warming ($\Delta T > 3.5$ K)		
		10%	20%	30%	10%	20%	30%	10%	20%	30%
10°–25°S	10%	2035	2066	—	2028	2057	2079	2023	2049	2067
	90%	2066	—	—	2051	2088	—	2043	2068	2087
Southern Africa	10%	2019	2054	2066	2016	2039	2058	2012	2035	2046
	90%	2045	2087	—	2045	2074	2093	2040	2064	2072
Central South America	10%	2065	—	—	2050	—	—	2042	—	—
	90%	—	—	—	2079	—	—	2074	—	—
15°–30°N	10%	2044	—	—	2036	2078	—	2038	2067	2097
	90%	2073	—	—	2066	—	—	2057	2083	—
East Asia	10%	2045	2078	—	2037	2062	—	2036	2058	2087
	90%	2085	—	—	2068	—	—	2063	2087	—
Southern North America	10%	—	—	—	2065	—	—	2052	2087	—
	90%	—	—	—	—	—	—	2086	—	—
50°–65°N	10%	2035	2070	—	2030	2059	2099	2031	2058	2084
	90%	2092	—	—	2068	—	—	2055	2086	—
Northern Eurasia	10%	2021	2076	—	2013	2055	—	2009	2050	2083
	90%	—	—	—	2062	—	—	2059	2082	—
Northern North America	10%	2013	2054	2069	2029	2048	2061	2016	2041	2059
	90%	2099	—	—	2086	—	—	2061	2076	2091

several decades (Table 7). However, response to warming of the timing of the 90% proportion is similar to that based on ensemble means. The timing of the 90% proportion is advanced with increased warming for all regions and thresholds of fractional change (Table 7). This implies that the timing in the high-warming group makes the habitat change sure to occur earlier, regardless of the uncertainty in future projections.

Figure 6 shows the projected time (year) of the plant habitat change, along with the GDP per capita values of the six nations for the three warming groups and thresholds of fractional change. For all thresholds and warming groups, the timings of plant habitat change in Botswana are substantially earlier than the other five countries by several decades (Figs. 6a,b). In particular, only Botswana shows the timings of plant habitat change for the low-warming group at the 30% threshold (Fig. 6c). The GDP per capita of Botswana is much smaller than the other nations, except China (Table 2). Thus, the vulnerability of plant habitat in Botswana is amplified, considering both the timing of plant habitat change and regional economic capability, which is essential for carrying out mitigation plans.

For the 10% and 20% thresholds, the timings of China are similar to those of Canada and Russia in all warming groups (Figs. 6a,b). However, China shows the smallest GDP per capita among the 6 countries, whereas the GDPs per capita of Canada and Russia are larger than those of the other 4 countries (Table 2). Thus, the plant habitat of China is more vulnerable to global warming than those of Canada and Russia because of low economic capability. For Mexico and Brazil, the timings of plant habitat change are later than those of other regions by several decades in all warming groups at the 10% threshold (Fig. 6a). Moreover, the fractional changes are less than 20% in Mexico and Brazil until 2099 for all warming groups, indicating a relatively low risk of plant habitat change (Fig. 6b). In addition, the large GDP per capita values of these two nations [$>10\,000$ US dollars (USD)] also decrease the adverse effects of plant habitat changes.

4. Discussion

Before evaluating the timing for specified plant habitat changes, we have analyzed the spatial patterns of plant habitat changes in terms of the global warming magnitude. In the low-warming group ($\Delta T < 2.5$ K), the largest spatial changes in plant habitat are projected in the boundary regions between the tropical (10° – 25° S), temperate (15° – 30° N), and boreal (50° – 65° N) habitats. For larger warmings [the medium group (2.5 K $< \Delta T < 3.5$ K) and the high group ($\Delta T > 3.5$ K)], the fractional

Timing of habitat change with GDP per Capita

FIG. 6. Timing when averaged plant habitat change reaches the (a) 10%, (b) 20%, and (c) 30% threshold, with the GDP per capita 2013 of Botswana, China, Mexico, Russia, and Canada. Dots represent low- (blue), medium- (yellow), and high-warming (red) thresholds.

changes in the plant habitat increase in all three latitude bands. For example, in the region 50° – 65° N, the boreal habitats are projected to decrease by 15.3%, 22.9%, and 32.3% in the low-, medium-, and high-warming groups, respectively. These results are consistent with the spatial patterns of the simulated plant habitat changes in previous studies (Cramer et al. 2001; Lucht et al. 2006; Sitch et al. 2008; Gonzalez et al. 2010; Jiang et al. 2012).

Estimating the timing of plant habitat changes due to global warming is one of the most important concerns,

and our capabilities to do so need to be improved. Here, we first estimate the timing of plant habitat changes using dominant spatial patterns of plant habitat changes over the globe. The timing of plant habitat changes is suggested for the three warming groups by specific years when specified amounts of changes (10%, 20%, and 30%) will occur in the three latitudinal belts. Regardless of the warming magnitude, the fastest plant habitat changes appear in the region 10°–25°S. For the medium-warming group, the plant habitat change in the latitude band 10°–25°S exceeds 20% in 2068, faster than for the latitude bands 15°–30°N and 50°–65°N by 27 and 17 yr, respectively (Table 6). In addition, the latitude band 10°–25°S shows significant regional variations in the timing of plant habitat change. In southern Africa, the plant habitat change is projected to reach 30% in 2094 in the low-warming group; in central South America, the projected plant habitat change remains <20% in the twenty-first century, even for the high-warming group (Table 6). Furthermore, for all warming groups and thresholds of fractional habitat change, the southern Africa region shows the fastest plant habitat changes (Table 6), suggesting that the plant habitat in southern Africa is most vulnerable to climate change.

Despite the use of ensemble mean climate projections, the timing of plant habitat change still has uncertainties due to inter-GCM variations. The uncertainties in the projected timing of plant habitat change are represented by colored bars in Fig. 5. Because of the uncertainty, the timing of plant habitat is reestimated using both tolerant and strict standards: the 10% and 90% proportions of model projections (Table 7). Compared to the timing based on the ensemble means, the timing of plant habitat change is advanced and delayed by several decades for the 10% and 90% proportion, respectively (Table 6 versus Table 7). This implies that the projected timing based on the ensemble mean includes large uncertainties. Nevertheless, there is consistency in the projected timing of plant habitat change, regardless of the standards that increased warming advances the timing of plant habitat change. A specific amount of plant habitat change appears earlier in southern Africa and East Asia than in the Americas in the same latitudinal bands. Thus, the timing of plant habitat change can be a good indicator representing the regional vulnerability of an ecosystem in response to climate change, regardless of the uncertainty of future projections.

The estimated timing of the plant habitat change presented in this study can help in planning mitigation policies, as many mitigation policies are developed for specific levels of climate change (UNFCCC 2009; Joshi et al. 2011). Nevertheless, implementation of

these mitigation policies requires economic considerations (Naidoo and Ricketts 2006; Adger et al. 2007a). Countries with weaker economic power are more vulnerable to plant habitat changes. We note that southern Africa has a low GDP per capita and very fast timing of plant habitat change. In southern Africa, Botswana shows the highest GDP per capita of 7317 USD, which is only 75th in position among all nations in the world (The World Bank 2013). The GDP per capita of the four southern African nations Madagascar, Mozambique, Zambia, and Zimbabwe is below 1800 USD, less than a quarter of Botswana's (Table 2). Thus, nations in southern Africa are likely to experience greater economic hardships in coping with fast habitat changes and subsequent ecological problems unless they achieve great economic development in a very short time. Support from the international community will be needed to mitigate the vulnerability of habitat change in southern Africa.

Information on the timing of plant habitat changes presented in this study will help to decide the optimum timing for implementing future ecosystem management policies. If plant habitat changes are reduced by timely management practice, many ecological advantages can be expected. For example, well-preserved plant habitats can protect terrestrial biodiversity from climate change because of the direct relationship between plant habitats and biodiversity (Fischlin et al. 2007; Giam et al. 2010; Bellard et al. 2012). Conservation of biodiversity can greatly benefit human society, as biodiversity is closely related to the ability of an ecosystem to supply goods and services (Cardinale et al. 2012) and is known to protect human society from the impact of climate change (Das and Vincent 2009; Turner et al. 2009; Nilsson and Persson 2012). In addition, regional impacts of global warming may be reduced through vegetation–climate feedback (Bonan 2008; Jackson et al. 2008). For instance, abrupt climate change and frequency of extreme weather may be prevented in future climates by conserving plant habitats (Bounoua et al. 2010; Jeong et al. 2010).

This study is limited in some aspects. Since the bioclimate rule is based only on surface temperature, other important factors, such as interspecies competition, physiological flexibility, and the effects of other climate variables, are not included in the plant habitat changes projected in this study. Furthermore, eight types of plant habitats based on the bioclimate rule may be too simplistic for representing numerous types of plants, in comparison to ecological niche models (Pearson and Dawson 2003; Morin and Thuiller 2009). Human-induced land-cover changes (or land use) can also play an important role in future changes in plant habitats

(Foley et al. 2011; Lambin and Meyfroidt 2011). Despite these limitations, which will be improved in future studies, the habitat changes projected in this study based on the bioclimate rule are generally consistent with previous studies (Cramer et al. 2001; Scholze et al. 2006; Sitch et al. 2008; Jiang et al. 2012), especially the latitudinal patterns in the plant habitat changes in previous studies on ecological responses to climate changes (Rosenzweig et al. 2008; Dillon et al. 2010). The three latitudinal zones, which are the main analysis domains in this study, also generally agree with regions with high vulnerability to warming (Scholze et al. 2006; Williams et al. 2007; Gonzalez et al. 2010). From a global perspective, the projected timing of habitats changes is thus acceptable as one reference for designing policies for future forest management.

5. Summary

This study examines the temporal side of future plant habitat change by estimating the timing of particular amounts of plant habitat change and its regional variations for three global model groups categorized according to the magnitude of warming for given emissions levels. Based on the timing to achieve specified amounts of habitat changes, the fastest plant habitat change is projected for southern Africa, a region with very weak economic power in the present day. Thus, the vulnerability of plant habitats in southern Africa will increase with continued warming, with potentially terrible economic and ecological consequences. Southern Africa will need the combined efforts of other nations to help mitigate the sudden plant habitat change and its impact on ecosystem and climate.

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