Habitat Suitability Under Changing Climatic Conditions for the Exotic Ambrosia Beetle, *Cnestus mutilatus* (Curculionidae: Scolytinae: Xyleborini) in the Southeastern United States

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ABSTRACT The camphor shot borer, *Cnestus mutilatus* (Blandford) is a nonnative ambrosia beetle first reported in the United States in 1999 at Oktibbeha County in Mississippi. Although, *C. mutilatus* is a major pest of several trees in its native habitat in Asia, it is not yet a major pest in the United States. However, the range expansion in recent years across the southeastern region indicates that *C. mutilatus* could be adapting quickly to the new environment, perhaps because of the availability of numerous host trees and suitable environmental conditions that support the population. As the population increases, future outbreaks of *C. mutilatus* may result in mortality of valuable hosts. Our objective was to identify potential suitable habitats for *C. mutilatus* in the southeastern United States under changing climate by 2020 and 2060 by examining *C. mutilatus* preferred conditions, host environmental requirements, precipitation, and temperature projections from an ensemble of general circulation model, and Intergovernmental Panel on Climate Change future climate scenarios. Our results indicated that suitable habitat for *C. mutilatus* in the southeastern United States will expand slightly under the A1B emission scenarios (i.e., moderate population growth and high-energy use balanced across all sources), and significantly under B1 emission scenarios (i.e., representing moderate population growth and an emphasis on global approaches to economic and environmental stability) by 2060. Whereas the opposite may occur under the A2 scenario (i.e., representing continuously increasing population, regionally focused economic growth, and slower introduction of alternative fuels technology). Nearly half of the parishes in Louisiana and counties in Mississippi will be suitable for *C. mutilatus* by 2020, under the A2 emission scenarios. However, suitable habitat range could decrease and become fragmented by 2060. These results could be useful in forest management efforts in places where *C. mutilatus* may become established in the future.

KEY WORDS ambrosia beetle, camphor shot borer, invasive species

The camphor shot borer, *Cnestus mutilatus* (Blandford) (Coleoptera: Curculionidae: Scolytinae: Xyleborini), is a nonnative ambrosia beetle first reported in the United States during 1999 from Oktibbeha County, MS (Schiefer and Bright 2004). *C. mutilatus* is native to Asia (Wood and Bright 1992), where it is a major pest of several tree hosts in its native habitat. Hosts include Chinese chestnut, *Castanea mollissima* Blume; maple, *Acer sieboldianum* Miquel, *Parabenzion trilobum* (Siebold & Zuccarini) Nakai, and silky oak *Grevillea robusta* Allan Cunningham ex Robert Brown (Sreedharan et al. 1991, Kajimura and Hijii 1992, 1994, Tang 2000). Since being reported in Mississippi, the beetle has been reported in Louisiana (Carlton and Bayless 2011) and several other southeastern states (Cognato et al. 2006, Gandhi et al. 2009, Leavengood 2013, Oliver et al. 2012, Werle et al. 2012). Range expansion in the southeast in recent years is likely because of availability of numerous host trees in the region and suitable environmental conditions that support populations of *C. mutilatus*. Hosts in North America include red maple (*Acer rubrum* L.), sugar maple (*Acer saccharum* Marshall), smooth Japanese maple (*Acer palmatum* (Thunberg) Murray), American hophornbeam (*Ostrya virginiana* (Miller) K. Koch), flowering dogwood (*Cornus florida* L.), American beech (*Fagus grandifolia* Ehrhart), American sweetgum (*Liquidambar styraciflua* L.), hickory (*Carya* spp.), American tulip tree (*Liriodendron tulipifera* L.), Chinaberry tree (*Melia azedarach* L.), loblolly pine (*Pinus taeda* L.), black cherry (*Prunus serotina* Ehrhart), American plum (*Prunus americana* Marshall), winged elm (*Ulmus alata* Michaux), and muscadine (*Vitis rotundifolia* Michaux) (Stone et al. 2007).

As climatic conditions change, the number of abnormally hot days is expected to increase in southern United States, with the largest temperature increases occurring during summer, potentially increasing the

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likelihood of intense droughts and wildfires (Karl et al. 2009). This projection likely will affect populations of insect pests in the southeast, including *C. mutilatus*. Therefore, a significant shift in the population of *C. mutilatus* in the United States is possible during the next few decades, especially if changing climate creates favorable conditions needed for population growth. Increases in populations of *C. mutilatus* may have direct and indirect effects on forest ecosystems, forest tree nurseries, and urban host plants as it spreads beyond current boundaries to new habitats. *C. mutilatus* is a polyphagous beetle that reproduces on numerous hosts (Lindgren 1990, Maeto et al. 1999) and has low host specificity (Stone et al. 2007), giving it a competitive ability to spread considerably beyond current locations. Although the beetle is currently not a major pest, future population increases may lead to outbreaks, resulting in mortality of valuable hosts, forest disturbance and fragmentation, and a reduction in host vitality (Volney and Fleming 2000, Pimentel et al. 2004, Stadler et al. 2005).

The objective of this study was to confirm the increasing abundance of *C. mutilatus* in Louisiana and identify potential suitable habitats in the southeastern United States under changing climate, based on *C. mutilatus* preferred conditions and host environmental requirements. We used precipitation and temperature projections from an ensemble of general circulation model (GCM; Olatinwo et al. 2013, Randall et al. 2007) and the Intergovernmental Panel on Climate Change (IPCC; IPCC 2007) future climate scenarios to develop range expansion models for the species by 2020 and 2060.

Materials and Methods

Ambrosia Beetles Trapping. To examine the increasing abundance of *C. mutilatus* populations in central Louisiana, traps were set up at two sites (A: 31° 21′24.64″ N, 92° 26′0.04″ W, and B: 31° 21′29.32″ N, 92° 26′8.62″ W) in Pineville, LA. Live ambrosia beetles (Curculionidae: Scolytinae) were collected from funnel traps baited with 95% ethanol between 23 February and 30 March 2012. The number of ambrosia beetles caught in the traps were counted and identified. The proportion (%) of each species relative to the total number of ambrosia beetles caught during the trapping period was calculated. Voucher specimens of all taxa are deposited in the Louisiana State Arthropod Museum, Baton Rouge, LA.

Precipitation and Temperature Projections. For this study, downscale data of annual precipitation and monthly temperature projections for 1,342 counties in 13 states—Arkansas, Alabama, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, and Virginia—were provided by the Climate Change Adaptation and Mitigation Management Options (http://www.srs.fs.usda.gov/factsheet/482) project, Southern Research Station, U.S. Department of Agriculture-Forest Service. Annual precipitation and monthly temperature projections data at the county level were computed from an ensemble of four GCM models: 1) the third generation coupled global climate (CGCM3) model; 2) the Geophysical Fluid Dynamics Laboratory model (GFDL); 3) the Community Climate System model, version 3 (CCSM3); and 4) the Hadley Centre Coupled model, version 3 (HadCM3). Two weather parameters were computed under the IPCC Special Report on Emissions Scenarios (SRES; IPCC 2007). The SRES represents different socioeconomic scenarios of future world development, where each scenario "describes a different world evolving through the 21st century, and each may lead to quite different greenhouse gas (GHG) emissions trajectories" (http://www.ipcc.ch/ipccreports/tar/wg2/index.php?idp = 154). Three scenarios used in this study were 1) A1B representing moderate population growth and high-energy use balanced across all sources; 2) A2 representing continuously increasing population, regionally focused economic growth, and slower introduction of alternative fuels technology; and 3) the B1 representing moderate population growth and an emphasis on global approaches to economic and environmental stability.

Preferred Conditions for *C. mutilatus*. According to CABI (2013) , *C. mutilatus* prefers temperate-mesothermal climate where the average temperature of the coldest month is >0°C and <18°C, and the warmest month temperature is >10°C (http://www.cabi.org/isc/datasheet/57239), a condition that matches the typical climatic conditions found in the southeastern United States. Therefore, for this study, we chose January as the coldest and July as the warmest month. Hence, suitable habitats for *C. mutilatus* were identified when preferred conditions are met in a county or parish based on the following two equations (1) and (2):

C. mutilatus =

{January mean temperature >0°C and <18°C;

July mean temperature >10°C; and

Annual total precipitation >1,500 mm} [1]

Hosts =

{January mean temperature [*lower limit*];

July mean temperature [*upper limit*]}

and {annual precipitation [*lower limit*];

annual precipitation [*upper limit*]} [2]

Precipitation and temperature requirements and limits for *C. mutilatus* hosts obviously vary significantly because of the broad host range (Table 1). Therefore, the coldest (lower) and the warmest (upper) limits in January and July were used to establish boundaries for the hosts in the southeast. Preferred conditions for *C. mutilatus* (1) and hosts species environmental requirements (2) were used as inputs in producing suitable habitat maps, where 1 and 0 indicate suitable and unsuitable habitat, respectively. To validate the *C. mutilatus* preferred conditions with actual observations, a map of predicted suitable habitat for *C. mu-*

Table 1. Temperature and precipitation requirements (lower and upper limits) for some *C. mutilatus* hosts in North America (Burns and Honkala 1990)

	Temperature limits (°C)		Precipitation limits (mm)	
	Jan. (lower)	July (upper)	Annual (lower)	Annual (upper)
A. saccharum (sugar maple)	−18.0	27.0	510	1020
Carya illinoensis (Wangenheim) K. Koch (Pecan)	−1.0	27.0	760	2010
Juglans nigra L. (black walnut)	−43.0[a]	19.0	640	1780
L. styraciflua (Sweet gum)	−1.0	38.0	1020	1520
L. tulipifera (tuliptree)	−7.2	27.2	760	2030[a]
O. virginiana (American hophornbeam)	−18.0	29.0	460[a]	1630
P. taeda (loblolly pine)	4.0	38.0[a]	1020	1520
Pr. serotina (black cherry)	−11.0	29.0	970	1120

[a] The upper and lower limits for hosts used for producing maps of suitable habitat.

tilatus in the southeastern United States was produced for 2003. *C. mutilatus* preferred weather conditions (equations 1 and 2) was overlay with actual observations from Lindgren funnel trap data reported by Schiefer and Bright (2004) in Mississippi in 2003.

Furthermore, maps of counties or parishes potentially suitable for *C. mutilatus* by 2020 and 2060 were produced using the temperature and precipitation projections by ensemble of four General Circulation Models (CGCM3, GFDL, CCSM3, and HadCM3) under three IPCC future climate scenarios (A1B, A2, and B1). Maps were produced in DIVA-GIS software ver. 7.5 (http://www.diva-gis.org/). Overlaps from host distributions based on equation (2) and the limits in Table 1 indicate a continuous availability of suitable hosts (in the southeast) to sustain changes in pest populations across the region by 2020 and 2060.

Results

C. mutilatus was the most abundant invasive ambrosia beetle species caught in funnel traps in Pineville, LA, during the period examined between February and March of 2012, accounting for 55% of the overall ambrosia beetles caught during the trapping period (Fig. 1). The result may indicate the emerging

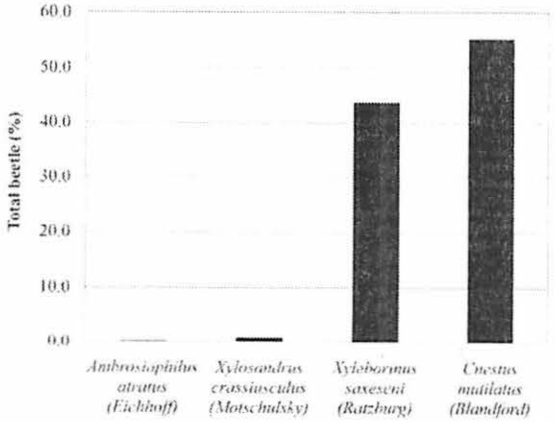

Fig. 1. The proportion of *C. mutilatus* compared with other ambrosia beetles caught in funnel traps between February and March 2012 in Pineville, LA ($n = 599$).

importance of monitoring the population growth of this invasive ambrosia beetle, as it adapts to new habitats in the southeastern United States. A map of suitable habitat for *C. mutilatus* in the southeastern United States produced using the *C. mutilatus* preferred conditions (equations 1 and 2), and funnel trap data reported by Schiefer and Bright (2004), showed that 13 of the 16 counties where *C. mutilatus* were collected in Mississippi were located within the suitable habitat range in 2003 (Fig. 2).

According to the ensemble GCM models projections, the number of counties or parishes with potential suitable habitat for *C. mutilatus* is expected to increase from 2020 to 2060 under A1B and B1 emission scenarios by ≈28 and 107 counties or parishes, respectively, and decrease under A2 by ≈145 counties or parishes (Table 2).

Under the A1B emission scenarios, suitable habitat for *C. mutilatus* is expected in ≈96 counties or parishes located in Alabama, Florida, Georgia, Louisiana, Mississippi, North Carolina, and Tennessee by 2020. The number of counties with suitable habitat is expected to increase to ≈124 counties or parishes by 2060 (Table 2), mostly in areas along the Gulf of Mexico coast, with likely expansion further north through the coastal plain, and a reduction in the number of suitable counties in southeast Florida (Fig. 3).

Under the A2 emission scenario, 230 counties or parishes are expected to be suitable for *C. mutilatus* by 2020. The number may decrease significantly to 85 counties or parishes by 2060 (Table 2), mostly in the Alabama, Louisiana, Mississippi, North Carolina, and Tennessee, with additional suitable counties in southeast Florida (Fig. 3).

Under the B1 emission scenario, 56 counties or parishes are likely to have suitable habitat for *C. mutilatus* in 2020, the lowest of the three scenarios. The number is projected to increase to 163 counties by 2060 (Table 2), mostly along the Gulf coast with substantial increases likely in Tennessee, north Alabama, and Georgia, and with some habitat fragmentation along the coastal plain (Fig. 3). Overall, the numbers of counties or parishes with potential suitable habitat for *C. mutilatus* will increase under the A1B and B1 emission scenarios from 2020 to 2060, and decrease under the A2 emission scenario during the same period.

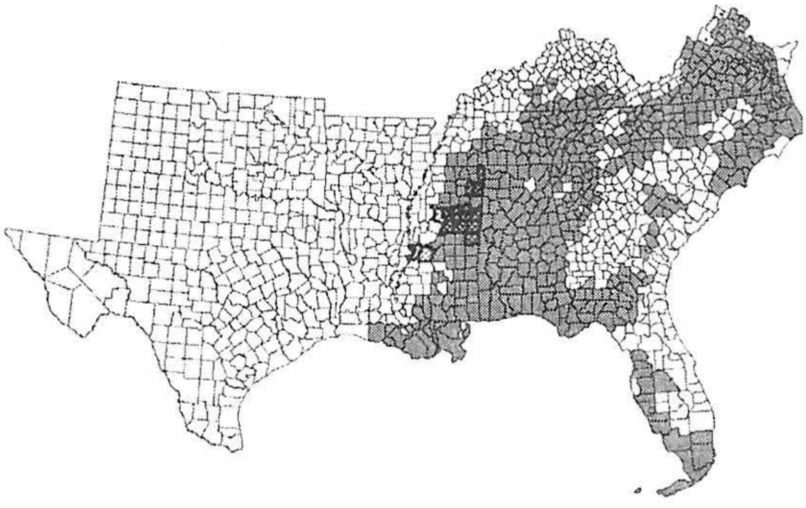

Fig. 2. The map of suitable habitat for *C. mutilatus* in the southeastern United States based on *C. mutilatus* preferred weather conditions (equations 1 and 2), overlay with the Lindgren funnel trap data reported by Schiefer and Bright (2004) in Mississippi in 2003. (Online figure in color.)

Discussion

C. mutilatus was the most abundant ambrosia beetle caught during the trapping period examined in the spring 2012 (Fig. 1). Although the beetle is not yet a major economic pest in the south, population increases may lead to future outbreaks, mortality of valuable hosts, forest disturbance and fragmentation, and reduction in host vitality. The above results in Louisiana in addition to increasing abundance reported by Schiefer and Bright (2004) in Mississippi makes identification of suitable habitat in southern forest ecosystems critical for future management efforts. Although the climatic conditions and the habitat range for *C. mutilatus* in the southeastern United States are not yet well-established, considering the diverse climatic conditions present in its native range, Schiefer and Bright (2004) suggested that the distribution of *C. mutilatus* may eventually encompass much of the eastern United States.

In the southeastern United States, suitable climatic conditions rather than unavailability of tree hosts will likely be the critical factor in the future distribution of *C. mutilatus* similar to observations by Salinas-Moreno et al. (2004) for *Dendroctonus* species. Therefore, the threat of future increases in *C. mutilatus* populations will depend greatly on how well it adapts to shifts in climatic conditions (i.e., temperature and precipitation requirements and limits), and its ability to successfully interact with available host plant species and other associated organisms within the forest ecosystem under the new regime.

Table 2. The number of counties or parishes suitable for *C. mutilatus* in the southeastern United States under three climate scenarios by 2020 and 2060

SRES scenarios	Suitable county or parish	
	2020	2060
A1B	96	124
A2	230	85
B1	56	163

A study by Karl et al. (2009) projected that the average temperatures are likely to rise by 2.5°C in the south under lower emissions projections, and to 5.0°C under higher emissions projections, with an increase of ≈5.8°C in summer based on climate projection for 2080. Karl et al. (2009) indicated a likelihood of less rainfall during winter and spring in states bordering the Gulf of Mexico compared with states farther north, which may result in droughts and water loss in plants, reducing host growth and vigor. Weakened host plants may trigger outbreaks of beetles, causing extensive damage across a broad range of hosts throughout the region.

Our results indicate that the distribution of potential suitable habitat for *C. mutilatus* in the southeastern United States will expand slightly under the A1B and significantly under B1 emission scenarios by 2060, whereas the opposite may occur under the A2 scenario. Under the A2 emission scenario, nearly half of parishes in Louisiana and counties in Mississippi (i.e., in the south and central parts of the states) will be suitable for *C. mutilatus* by 2020. However, the suitable habitat range is expected to decrease and become fragmented by 2060. Although significant differences are expected in annual precipitation and monthly temperature projections under the three climate scenarios examined, annual precipitation >1,500 mm is a key

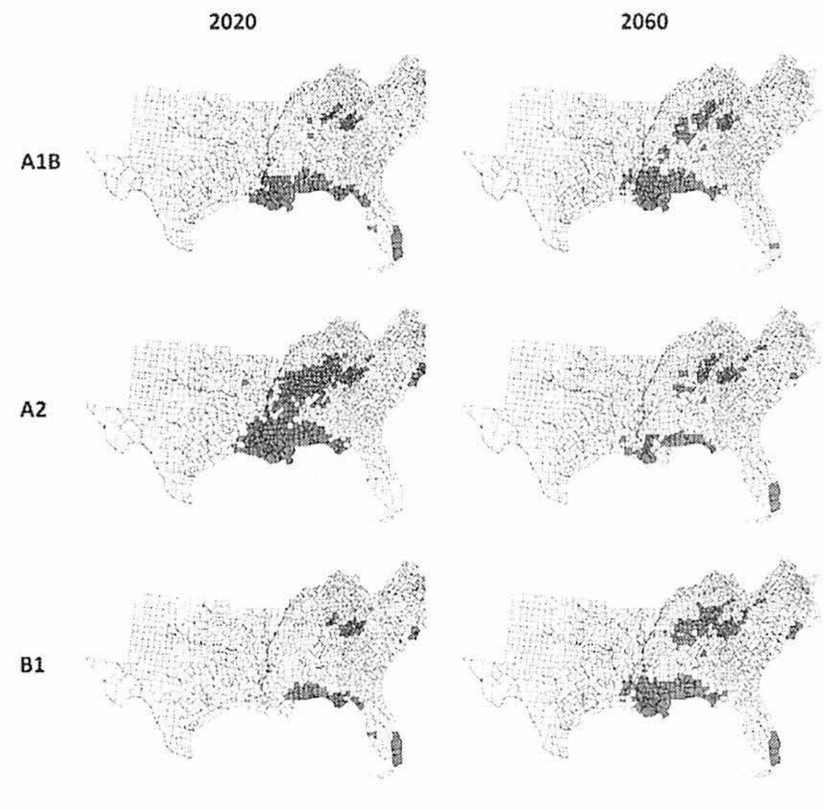

Fig. 3. Counties with potential suitable habitat for *C. mutilatus* in the southeastern United States, under A1B, A2, and B1 emission scenarios by 2020 and 2060 based on the mean monthly temperature and annual precipitation projections from ensemble of four GCMs (CGCM3, GFDL, CCSM3, and HadCM3). (Online figure in color.)

factor in the distribution of *C. mutilatus* suitable habitat across the southeast, especially because *C. mutilatus* will likely have continuous access to several host species through 2060 (Fig. 3). Under the A2 emission scenario, there are no counties in southern Florida with precipitation >1,500 mm by 2020, making that region potentially less suitable in 2020, compared with the same period under the A1B and B1 (Fig. 3).

Weather parameters such as the number of days with peak temperatures >32.2°C per year is projected to rise significantly under higher emission scenario (Karl et al. 2009), resulting in higher annual average temperature. Shugart (2003) noted an increase in temperature of ≈2°C over several thousand years led to significant changes in the composition and formation of new forest communities, most of which no longer exist today. An increase in future temperature under A2 may be sufficient to caused forest fragmentation in parts of the southern forest ecosystems.

Changes in climate may have measurable impacts on seasonal weather conditions, insect populations, host physiology, and host range distributions (Bentz et al. 2010). Therefore, growth, distribution, and survival of *C. mutilatus*, as with many insects, will depend directly or indirectly on favorable conditions, particularly, because insect developmental stages, adult emergence, flight, and longevity may be affected by temperature. Changes in climatic conditions could enable nonnative species to adapt to shifts in seasonal temperature (Balanyá et al. 2006, Bradshaw and Holzapfel 2006) in their new habitat, thereby facilitating range expansions into the new niches created by favorable temperatures (Battistia et al. 2006, Nealis and Peter 2009).

Studies have linked outbreaks of bark beetles to shifts in temperature and precipitation resulting from species high sensitivity to changes in temperature and water stress (Berg et al. 2006, Powell and Logan 2005). Generally, warmer conditions may accelerate insect feeding, development, and movements, which in turn affects the rate of fecundity, survival, generation time, and dispersal (Bale et al. 2002). Warmer winters, for example, may facilitate removal of existing range barriers, allowing nonnative insects to spread beyond current locations into places where hosts are abundant, thereby resulting in direct competition with native insect species.

In this study, we focused solely on temperature and precipitation projections in producing the suitable habitat maps discussed. The complexity of insect species' responses to climate change may result in uncertainties in predicting the extent and nature of impacts. However, predicted changes in temperature from various GCM models serve as an important basis for estimating habitat responses to changing climate conditions. The SRES scenarios, the GCM models, coupled with the preferred environmental parameters used for *C. mutilatus* and associated hosts in this study; at the minimum, they provide some insight into how nonnative pest habitats could respond to climate change within the southeastern United States forest ecosystems. Results from this study may be useful in long-term forest management efforts in places where *C. mutilatus* may become established in the future.

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