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Is Chinese Tallowtree, *Triadica sebifera*, an Appropriate Target for Biological Control in the United States?

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Biological control is one of the most common approaches used to manage invasive weeds of wetlands and other natural areas. Before candidate agents can be released, research is conducted to support biological control, which can be protracted and expensive, leading to a scientific and potentially lengthy regulatory review. To increase biological control safety, efficacy, and transparency, we suggest that during the early phases of a weed project, the feasibility of the invasive plant as a target should be studied explicitly. Our purpose here is to summarize information of an important invasive weed that can serve to judge whether the project is appropriate. Chinese tallowtree, *Triadica sebifera*, is one of the worst invasive species invading coastal wetlands and other riparian areas of the southeastern United States. Current management practices have not controlled the spread of this weed into these sensitive habitats. Initial surveys in the plant's native Chinese range for potential biological control agents have recovered several herbivore species that could be developed. These potential agents include defoliators, root and foliage feeders, and gall formers, whose biology, apparent host specificity, and impacts on plant fitness suggest that biological control offers great promise against Chinese tallowtree. When conducted during the initial phase of a project, this type of feasibility study can address potential conflicts of interest and risks, ultimately producing projects that are more effective and safer for biological control.

Nomenclature: Chinese tallowtree, *Sapium sebiferum* (L.) Roxb., *Triadica sebifera* (L.) Small.

Key words: *Bikasha collaris* (Baly), classical biological control of weeds, integrated control, invasive species.

Introduction

Wetlands are some of the most valued and yet threatened habitats in the world. They provide many ecological, economic, and social benefits, including flood abatement, improved water quality, and support for biodiversity (Engelhardt and Ritchie 2001; Zedler 2003). Wetlands contribute as much as 40% of these ecosystem services to Earth's life support system (Costanza et al. 1997; Zedler 2003). Worldwide, wetlands occupy more than 330,000,000 ha (815,000,000 ac), and although many of the environmental services are difficult to calculate, they contribute at least \$14,785 ha^{-1} yr^{-1} (Costanza et al. 1997). Despite their high value, wetland communities are some of the most susceptible to invasive species (Zedler and Kercher 2003).

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The ecosystem services provided by wetlands are threatened by a number of factors, including physical removal for development and the establishment of invasive plants. As a definition, invasive plants and animals are those that rapidly increase their spatial distribution by expanding into native plant communities (Richardson et al. 2000). Invasive plants constitute threats to ecosystems, economic activity, and human welfare (Mack et al. 2000). They are among the greatest threats to biodiversity, ecosystem function, and recreational uses of natural areas. Invasive plants also constitute one of the greatest threats to rare, endangered, and threatened species (Zavaleta 2000).

Chinese tallowtree, *Triadica sebifera* (L.) Small (= *Sapium sebiferum* (L.) Roxb.), hereafter tallow, invades coastal prairies, riparian areas, flood plains, wetlands, and lake margins of agricultural areas, forestlands, and natural areas (Bruce et al. 1997; Jubinsky and Anderson 1996). Conventional methods of control (mechanical, physical, chemical) of tallow have been unable to curb the spread of this invasive weed. Biological control involves the introduction of host-specific herbivores from the area of origin of the weed. This method can provide an ecologically sound, cost effective, and sustainable management solution to protect native plants in these habitats. Successful biological control programs can reduce biomass of the target weed (Hoffmann and Moran 1998; McEvoy et al. 1991; Tipping et al. 2012) to levels that allow recovery of native plants (Rayamajhi et al. 2009).

Several hypotheses have been proposed to explain invasiveness in plants (Rejmánek 2000); among them is the enemy-release hypothesis. This hypothesis predicts that exotic species are released from their natural enemies when introduced into new areas, and these populations experience increased distribution and abundance with little biotic regulation (Keane and Crawley 2002). This hypothesis is a key component of the management of invasive species with biological control (Jongejans et al. 2006; Keane and Crawley 2002). Classical biological control aims to reunite exotic invasive species with natural enemies from a weed's native range. Through host specificity testing both in the agent's native range and in quarantine, the host range of potential agents is determined prior to release (Van Driesche et al. 2008). This testing generally begins by determining the susceptibility of the valued plant species most at risk. Compiling molecular phylogenies becomes critical as the species most closely related to the weed are thought to share similar morphology and secondary plant chemistry (Ehrlich and Raven 1964; Mitter and Farrell 1991). Plants that have secondary chemistry and other physical qualities similar to the target weed are given highest priority in the prerelease testing protocol to determine their vulnerability to nontarget damage (Bernays and Chapman 1994).

The safety of biological control has been the subject of considerable discussion recently (Louda et al. 2003; McEvoy and Coombs 1999; Moran et al. 2005). This concern for the safety toward valued plants has been held by biological control scientists for decades (Dodd 1940) and this continues especially toward economic and native plants (Van Driesche et al. 2010). An open discussion of the benefits and concerns of specific biological control projects during their initial phases can increase transparency of the practice, invite discussion, and ultimately improve safety (Miller and Aplet 2005). Research on the basic biology of possible targets of biological control, with the explicit aim of evaluating the feasibility of implementing biological control, can be used in presenting the public with a project's potential benefits and risks (Manrique et al. 2011; Wheeler et al. 2007). The goals here are to summarize (1) distribution, (2) taxonomy, (3) life history, (4) environmental damage, (5) risk to human health, (6) economic damage, (7) potential conflicts of interest, (8) current means of control, and (9) potential for biological control of tallow.

Distribution of Tallow

Tallow in Its Native Range. The native range of tallow includes parts of China, Japan, and northern Vietnam (Bingtao and Esser 2008). In China, it occurs mostly in provinces south of the Yellow River, including Anhui, Fujian, Gansu, Guangdong, Guangxi, Guizhou, Hainan, Hubei, Hunan, Jiangsu, Jiangxi, Shaanxi, Shandong, Sichuan, Taiwan, Yunnan, Zhejiang (Zheng et al. 2005) (Fig. 1).

Tallow in Its Invasive Range. Tallow was introduced to many countries around the world as a source of vegetable tallow. This species is known to be naturalized in Japan, Taiwan, Australia, India, Pakistan, Europe, Martinique and the Sudan (Bingtao and Esser 2008; Bruce et al. 1997; Hosking et al. 2003; Pattison and Mack 2008). Tallow has been introduced to the United States numerous times and into several different locations. It was first introduced into Savannah, GA and Charleston, SC in the late 18th century. In the early 20th century tallow was introduced and planted widely in many areas of the southeastern United States. The native sources of these introductions are genetically best matched to several western and southern Chinese populations (Bruce et al. 1997; Dewalt et al. 2011; Lieux 1975).

Since its introduction, the weed has been reported primarily in 10 states, including North Carolina, South Carolina, Georgia, Florida, Alabama, Mississippi, Louisiana, Arkansas, Texas, and California (Fig. 2) (Rawlins et al. 2013; U.S. Department of Agriculture—Natural Resources Conservation Service [USDA-NRCS] 2013). In Florida, tallow occurs primarily north of Tampa, Orlando, and Daytona Beach (Rawlins et al. 2013; Wunderlin and Hansen 2008). Additionally, its range extends west along the Gulf coast to south of Houston, Texas. These infestations extend north through Louisiana to southern Arkansas. A separate infestation is known in riparian areas of the Central Valley of California (Bower et al. 2009; Rawlins et al. 2013; USDA-NRCS 2013).

Climate models such as CLIMEX are frequently used to predict the potential geographical distribution of a species (Sutherst et al. 1999). The potential range of this weed is likely to expand 500 km beyond its current distribution based on CLIMEX projections (Pattison and Mack 2008, 2009). Climate models also predict that the most favorable area for tallow is southern Florida where the weed has not been widely reported (Pattison and Mack 2008; Wunderlin and Hansen 2008). With few biotic factors influencing range expansion, the key climatic variables limiting spread to the north and west include low temperature and limited precipitation, respectively (Pattison and Mack 2008). In California, the range of this species is expected to expand into areas immediately adjacent to perennial water sources in the Central Valley (Bower et al. 2009).

Taxonomy

One of the first steps in determining the safety of a potential biological control agent is to test the weed's

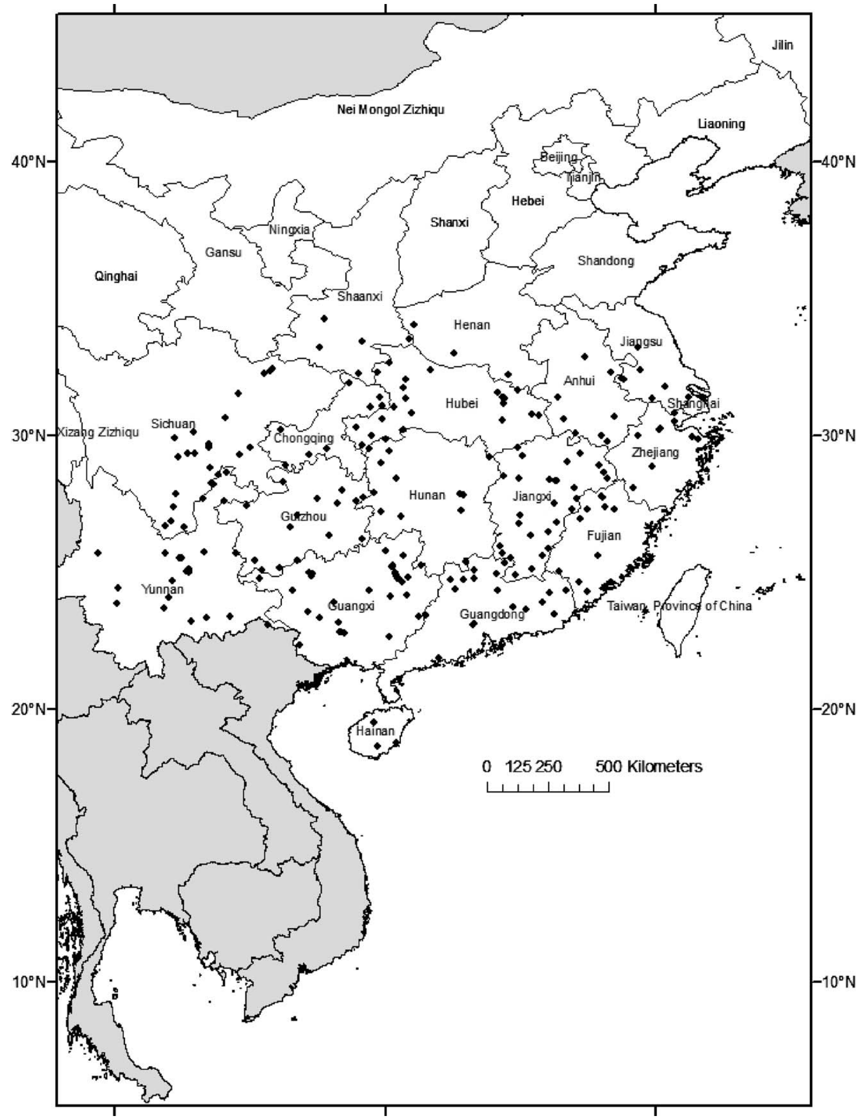

Figure 1. Distribution of tallow in China. Dots represent locations from herbaria collections and survey sites visited by the authors.

closest relatives to determine if they are suitable hosts (Wapshere 1974). Other species of the weed genus should be tested first, followed by progressively more distant taxa. The tallow taxon, *Triadica*, is a small genus in the Euphorbiaceae, subfamily Euphorbioideae, tribe Hippomaneae, and is endemic to eastern and southeastern Asia (Esser 2002). The genus is well circumscribed with only three accepted species and very probably monophyletic (Esser et al. 1997). The phylogeny used here follows that of Wurdack et al. (2005), Wurdack and Davis (2009), Govaerts et al. (2013), The Plant List (2013), and Riina and Berry (2013). The Euphorbiaceae family is one of the largest, containing about 6,300 species in 219 to 245 genera. In the United States, there are 60 genera (including the genera of Phyllanthaceae and Putranjivaceae) in the family and 596 accepted taxa (USDA-NRCS 2013). We include here the genera of the now distinct families Phyllanthaceae and Putranjivaceae, as they were previously included in the Euphorbiaceae (Angiosperm Phylogeny Group III [APG III] 2009). The family is organized into four subfamilies, of which only Acalyphoideae, Crotonoideae, and Euphorbioideae occur in the U.S. range of tallow (Table 1) (Stevens 2011; Wurdack et al. 2005). The Euphorbioideae subfamily has five tribes and 54 genera. In tallow's invasive range, only two tribes occur, the Hippomaneae and Euphorbieae. The first tribe, Hippomaneae, contains a single subtribe Hippomaninae, to which tallow is assigned. The tribe Euphorbieae also has a single subtribe in tallow's invasive range, Euphorbiinae. The species thought to be most vulnerable to nontarget damage by biological control agents are the close relatives, those assigned to the tribe Hippomaneae. Although the

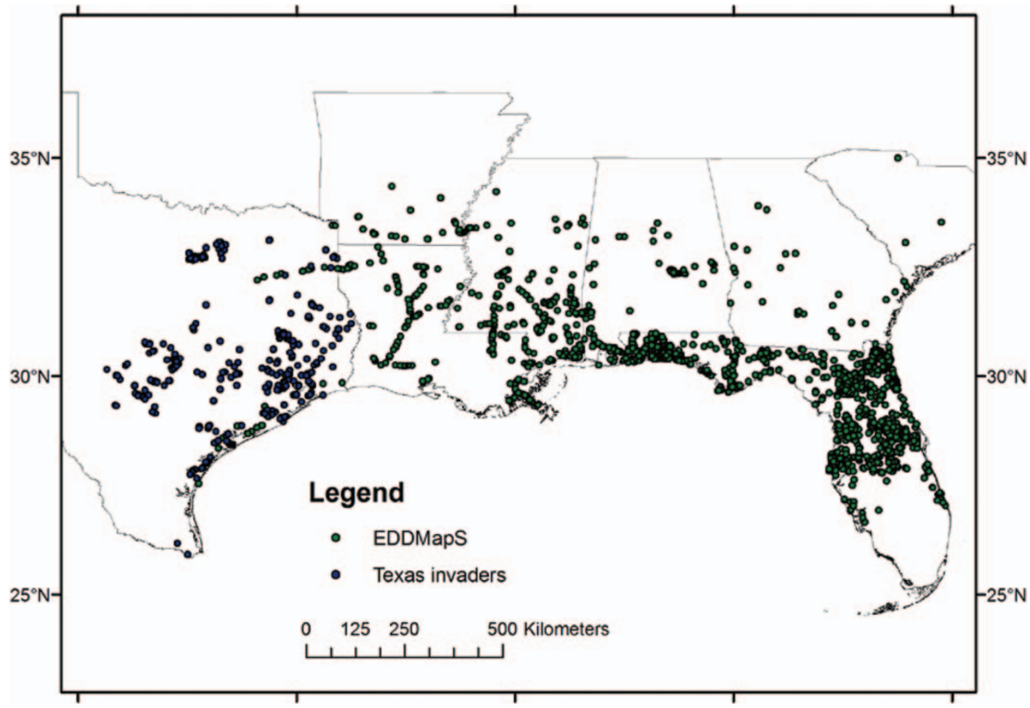

Figure 2. Current distribution of tallow in the southeastern United States. Gray (green) dots are locations where tallow has been reported on the EDDMaps database (Rawlins et al. 2013), solid black (blue) dots are from Texas Invasives.org (2013). (Color for this figure is available in the online version of this paper.)

susceptibility of these species will be the focus of host testing, species distributed throughout the family also will be tested.

Tallow was formally placed in the *Sapium* genus and upon revision reassigned to the Asian *Triadica* genus (Esser 2002). No members of the *Triadica* genus are native to the New World. Although geographically separated from the tallow infestation, two species from Puerto Rico, *Sapium laurifolium* (A. Rich.) Griseb. and *Sapium laurocerasus* Desf., are included here, as they are taxonomically close relatives of the weed (USDA-NRCS 2013) and could be vulnerable to biological control agents released from Florida (Pratt and Center 2012). A Mexican species, *Sapium macrocarpum* Müll. Arg., occurs well south of the tallow infestation (Chiapas, Oaxaca states; Tropicos.org) but because of its close affinity to tallow is a species of concern (Burger and Huft 1995). The South American species, *Sapium glandulosum* (L.) Morong, was collected in Pensacola, FL in 1901 (New York Botanical Garden [NYBG] 2013). However, this species should not be treated as part of the U.S. flora, as it is a single collection, a "waif," that was never recollected after more than 100 yr (P. Berry, personal communication, University of Michigan Herbarium; Nelson 2011). Other related North American species that will be high priorities for testing include *Gymnanthes lucida* Sw., *Hippomane mancinella* L., *Sebastiania bilocularis* S. Watson, *Ditrysinia* (=*Sebastiania*) *fruticosa* (Bartram) Govaerts & Frodin, and *Stillingia sylvatica* L. (Table 1). Additionally, of special concern are 5 federally listed and 17 state listed (Florida, Texas) threatened or endangered species (Table 1).

Life History

Tallows are deciduous trees that grow to 15 m tall (49 ft) (Zheng et al. 2005). In China, tallow occurs up to 1,200 m elevation and is tolerant of frost. It grows in a wide range of forest types, on different soils, under dry and moist conditions. In its native range, tallow is not known to be weedy (Zheng et al. 2005). In the United States, tallow is tolerant of shade, sun, drought, flood, freeze and salt conditions (Jones and McLeod 1989; Jubinsky and Anderson 1996). The tree is a monoecious species with separate male and female flowers that mature at different times (dichogamy), thus promoting cross pollination. Pollination occurs by generalist insects (Duke 2013). Seeds are dispersed by water or birds and may remain viable for 7 yr (Bruce et al. 1997). Plants may reproduce vegetatively, sprouting naturally and after being cut or burned (Bruce et al. 1997). A single tree can reproduce in 3 yr, and a mature tree can produce over 100,000 seeds per year (Bruce et al. 1997).

Tallow Genetic Variability. Multiple introductions from different sources often increase genetic diversity of

Table 1. North American and Caribbean species of Malpigiales that are native or introduced and considered for testing of prospective biological control agents of Chinese tallow. List compiled from Webster (1994), Wurdack et al. (2005), Wurdack and Davis (2009), Govaerts et al. (2013), and The Plant List (2013), Riina and Berry (2013).

Family (Subfamily)	Tribe	Subtribe	Species[a]	Authority	Common name	Listed species: United States Threatened (T)/Endangered (E)[b]	Listed species: State T/E[c]	Distribution[d]	Status
Euphorbiaceae (Euphorbioideae)									
	Hippomaneae								
		Hippomaninae	*Triadica sebifera* (=*Sapium sebiferum*)	(L.) Small	Chinese tallow			Southeastern United States, California	Introduced
			Gymnanthes lucida	Sw.	Oysterwood			Florida	Native
			Hippomane mancinella	L.	Manchineel		E	Florida	Native
			Sebastiania bilocularis	S. Watson	Arrow poison plant			Arizona	Native
			Ditrysinia (=*Sebastiania*) *fruticosa*	(W. Bartram) Govaerts & Frodin	Gulf Sebastian-bush			Southeastern United States	Native
			Sapium glandulosum[e]	(L.) Morong	Gumtree			Florida, Virgin Islands	Introduced
			Sapium laurifolium	(A. Rich.) Griseb.	Hinchahuevos			Puerto Rico, Central America	Native
			Sapium laurocerasus	Desf.	Milktree			Puerto Rico	Native
			Sapium macrocarpum	Mull. Arg.	Palo de leche			Mexico, Central America	Native
			Stillingia sylvatica	L.	Queen's-delight			Southeastern United States	Native
	Euphorbieae								
		Euphorbiinae	*Euphorbia conferta*	(Small) B.E. Sm.	Everglade Key sandmat			Florida	Native
			Euphorbia commutata	Engelm. ex A. Gray	Tinted woodland spurge		E	Eastern United States	Native
			Euphorbia (=*Chamaesyce*) *cumulicola*	(Small) Oudejans	Coastal dune sandmat		E	Florida	Native
			Euphorbia (=*Poinsettia*) *cyathophora*	Murray	Fire on the mountain			United States, Hawaii, Puerto Rico, Virgin Islands	Native

Table 1. Continued.

Family (Subfamily)	Tribe	Subtribe	Species[a]	Authority	Common name	Listed species: United States: Threatened (T)/Endangered (E)[b]	Listed species: State: T/E[c]	Distribution[d]	Status
			Euphorbia (=*Chamaesyce*) *deltoidea* subsp. *deltoidea*	Engelm. ex Chapm.	Wedge sandmat	E	E	Florida	Native
			Euphorbia (=*Poinsettia*) *deltoidea* subsp. *pinetorum*	(Small) Oudejans	Wedge sandmat		E	Florida	Native
			Euphorbia (=*Chamaesyce*) *garberi*	Engelm. ex Chapm	Garber's sandmat	T	E	Florida	Native
			Euphorbia graminea	Jacq.	Grassland spurge			California, >Florida, Hawaii, Louisiana	Introduced
			Euphorbia (=*Poinsettia*) *heterophylla*	L.	Mexican fireplant			Southeastern United States, Hawaii, Puerto Rico, Virgin Islands	Native
			Euphorbia (=*Chamaesyce*) *hirta*	L.	Pillpod sandmat			Southeastern United States, Hawaii, Puerto Rico, Virgin Islands	Native
			Euphorbia (=*Chamaesyce*) *hooveri*	L.C.Wheeler	Hoover's sandmat	T		California	Native
			Euphorbia (=*Chamaesyce*) *hypericifolia*	L.	graceful sandmat			Southeastern United States, Hawaii, Puerto Rico, Virgin Islands	Native
			Euphorbia (=*Chamaesyce*) *hyssopifolia*	L.	Hyssopleaf sandmat			Southeastern United States, Hawaii, Puerto Rico, Virgin Islands	Native

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Table 1. Continued.

Family (Subfamily)	Tribe	Subtribe	Species[a]	Authority	Common name	Listed species: United States: Threatened (T)/Endangered (E)[b]	Listed species: State: T/E[c]	Distribution[d]	Status
			Euphorbia (=*Chamaesyce*) *maculata*	L.	Spotted sandmat			United States, Canada	Native
			Euphorbia milii	Des Moul.	Christplant			Florida	Introduced
			Euphorbia (=*Chamaesyce*) *pergamena*	Small	Southern Florida sandmat		T	Florida	Native
			Euphorbia polyphylla	Engelm. ex Chapm.	Lesser Florida spurge			Florida, Louisiana	Native
			Euphorbia (=*Chamaesyce*) *porteriana*	(Small) Oudejans	Porter's sandmat		E	Florida	Native
			Euphorbia (=*Poinsettia*) *pulcherrima*	Willd. ex Klotzsch	Poinsettia			Puerto Rico, Hawaii, Mexico	Introduced
			Euphorbia telephioides	Chapm.	Telephus spurge	T	E	Florida	Native
			Euphorbia tirucalli	L.	Indiantree spurge			California, Hawaii, southwestern Florida, Puerto Rico, Virgin Islands	Invasive
			Euphorbia (=*Pedilanthus*) *tithymaloides*	L.	Redbird flower			Southeastern Florida, Puerto Rico, Virgin Islands	Native
	Hureae		*Hura crepitans*	L.	Sandbox tree			Florida, Puerto Rico, Virgin Islands	Native
Euphorbiaceae (Acalyphoideae)									
	Acalypheae								
		Acalyphinae	*Acalypha chamaedrifolia*	(Lam.) Mull. Arg.	Bastard copperleaf			Florida, Puerto Rico, Virgin Islands	Native
			Acalypha gracilens	A.Gray	Slender threeseed mercury			Eastern United States	Native
			Acalypha ostryifolia	Riddell ex J.M. Coult.	Pineland threeseed mercury			Southeastern United States, Puerto Rico, Virgin Islands	Native

Table 1. Continued.

Family (Subfamily)	Tribe	Subtribe	Species[a]	Authority	Common name	Listed species: United States: Threatened (T)/Endangered (E)[b]	Listed species: State: T/E[c]	Distribution[d]	Status
			Acalypha wilkesiania	Mull. Arg	Copperleaf			Florida	Introduced
		Ricinineae	*Ricinus communis*	L.	Castorbean			Southeastern United States, Hawaii, Puerto Rico, Virgin Islands	Invasive
	Chrozophoreae								
		Ditaxinae	*Ditaxis argothamnoides* (=*Argythamnia blodgettii*)	Bertol. (ex Spreng.) Radcl.	Blodgett's silverbush		E	Florida	Native
			Caperonia palustris	(L.) A. St.-Hil.	Sacatrapo			Southeastern United States, Puerto Rico, Virgin Islands	Introduced
	Plukenetieae								
		Dalechampiinae	*Dalechampia scandens*	L.	Spurgecreeper			Puerto Rico, Virgin Islands	Native
		Tragiinae	*Tragia saxicola*	Small	Florida Keys noseburn		T	Florida	Native
Euphorbiaceae (Crotonoideae)									
	Aleuritideae								
		Aleuritinae	*Vernicia* (=*Aleurites*) *fordii*	(Hemsl.) Airy Shaw	Tungoil tree			Southeastern United States, California, Puerto Rico	Introduced
	Codiaeae		*Codiaeum variegatum*	(L.) Rumph. ex A. Juss.	Garden croton			Puerto Rico	Introduced
	Crotoneae		*Croton alabamensis*	E.A. Sm. ex Chapm.	Alabama croton			Alabama, Texas, Tennessee	Native
			Croton linearis	Jacq.	Grannybush			Florida, Texas	Native
			Croton glandulosus	L.	Vente conmigo			Eastern United States, Puerto Rico, Virgin Islands	Native
			Croton humilis	L.	Pepperbush		E	Florida, Puerto Rico, Virgin Islands	Native

Table 1. Continued.

Family (Subfamily)	Tribe	Subtribe	Species[a]	Authority	Common name	Listed species: United States: Threatened (T)/Endangered (E)[b]	Listed species: State: T/E[c]	Distribution[d]	Status
			Croton punctatus	Jacq.	Gulf croton			Southeastern United States	Native
	Jatropheae		*Jatropha curcas*	L.	Barbados nut			Florida, Hawaii, Puerto Rico, Virgin Islands	Introduced
			Jatropha gossypifolia	L.	Bellyache bush			Florida, Hawaii, Puerto Rico, Virgin Islands	I/N
			Jatropha integerrima	Jacq.	Peregrina			Florida, Puerto Rico	Introduced
			Jatropha multifida	L.	Coralbush			Florida, Puerto Rico, Virgin Islands	Introduced
			Jatropha podagrica	Hook.	Goutystalk nettlespurge			Puerto Rico	Introduced
	Manihoteae		*Cnidoscolus texanus*	(Mull.Arg.) Small	Texas bullnettle			South-central United States	Native
			Cnidoscolus urens (=*stimulosus*)	(L.) Arthur	Finger rot			Southeastern United States	Native
			Manihot esculenta	Crantz	Cassava			Southeastern United States	Introduced
			Manihot grahamii	Hook.	Graham's manihot			Southeastern United States	Introduced
			Manihot walkerae	Croizat	Walker's manihot	E	E	Texas, Mexico	Native
Phyllanthaceae									
	Bischofieae		*Bischofia javanica*	Blume	Javanese bishopwood			Florida, Hawaii	Introduced
	Bridelieae		*Heterosavia* (=*Savia*) *bahamensis*	(Britton) Petra Hoffm.	Bahama maidenbush		E	Florida	Native
	Phyllantheae		*Breynia disticha*	J.R. Forst. & G. Forst.	Snowbush			Florida, Hawaii, Puerto Rico	Introduced
		Flueggeinae	*Flueggea virosa*	(Roxb. ex Willd.) Royle	Common bushweed			Puerto Rico	Introduced
			Glochidion puberum	(L.) Hutch.	Needlebush			Alabama	Introduced

Table 1. Continued.

Family (Subfamily)	Tribe	Subtribe	Species[a]	Authority	Common name	Listed species: United States: Threatened (T)/Endangered (E)[b]	Listed species: State: T/E[c]	Distribution[d]	Status
			Phyllanthus acidus	(L.) Skeels	Tahitian gooseberry tree			Florida, Hawaii, Puerto Rico, Virgin Islands	Introduced
			Phyllanthus amarus	Schumach. & Thonn.	Carry me seed			Florida, Puerto Rico, Virgin Islands	Introduced
			Phyllanthus liebmannianus	Mull. Arg.	Florida leaf-flower		E	Florida	Native
			Phyllanthus pentaphyllus	C. Wright ex Griseb.	Fivepetal leaf-flower			Florida, Puerto Rico	Native
			Phyllanthus tenellus	Roxb.	Mascarene Island leaf-flower			Southeastern United States, Hawaii, Puerto Rico	Introduced
			Phyllanthus urinaria	L.	Chamber bitter			Southeastern United States, Puerto Rico	Introduced
	Poranthereae		*Phyllanthopsis* (=*Leptopus*) *phyllanthoides*	(Nutt.) Voronts. & Petra Hoffm.	Missouri maidenbush			South-central United States	Native
Putranjivaceae			*Drypetes diversifolia*	Krug & Urb.	Milkbark		E	Florida	Native
			Drypetes lateriflora	(Sw.) Krug & Urb.	Guiana plum		T	Florida, Puerto Rico	Native

[a] Species names follow Riina and Berry (2013), The Plant List (2013).

[b] Federal endangered plant list from U.S. Fish and Wildlife Service Endangered Species Program (2006).

[c] Florida state endangered plant list from Weaver and Anderson (2010); Texas state endangered plant list from Texas Parks and Wildlife Department (2013).

[d] Distribution from USDA-NRCS (2013).

[e] Orphaned South American species no longer present in the United States.

introduced populations, and recombination events may give rise to novel genotypes with higher invasive potential than parental populations (Geiger et al. 2011; Lavergne and Molofsky 2007). Numerous hypotheses have been proposed to explain this, one of which suggests that invasive plants growing in the absence of specialized herbivores will be selected to decrease resources to antiherbivore defenses and allocate greater resources to growth and reproduction (Blossey and Nötzold 1995). Chinese tallow has been one of the invasive species that supports this hypothesis. When environmental variation was minimized by growing plants from different origins in a common garden, tallow plants from Louisiana and Texas had greater basal area than plants from China (Huang et al. 2010; Siemann and Rogers 2001). Additionally, the antiherbivore compounds, tannins, had lower concentrations in plants from Louisiana and Texas, and these levels were highest in plants from China (Siemann and Rogers 2001). Genetic analysis of the Chinese and U.S. tallow populations with microsatellite markers showed that the plants from the original introductions in Georgia and South Carolina differed substantially in their genetic composition and had greater genetic diversity than the rest of the southeastern United States (Dewalt et al. 2011). Laboratory and field experiments determined that specialist herbivores reared on the invasive tallow populations had higher growth, consumption, and densities than those fed Chinese plants (Huang et al. 2010; Wang et al. 2011). However, the invasive populations may be more tolerant and display compensatory growth following foliar damage and thus are able to withstand and survive a fixed level of herbivory without a corresponding reduction in fitness (Wang et al. 2011).

Environmental Damage

Chinese tallowtree invasions alter species composition, community structure, and ecosystem processes in many native habitats (Bruce et al. 1995, 1997). For example, in less than 10 years, native graminoids and forbs were replaced by tallow trees resulting in monospecific stands in an endangered coastal prairie of Louisiana and Texas (Bruce et al. 1995). This area is home to the federally endangered Attwater's prairie chicken (*Tympanuchus cupido attwateri* Bendire) and the wintering grounds for the federally endangered whooping crane (*Grus americana* L.) (Grace 1998). Moreover, tallow infestations negatively affect microfauna that break down leaf litter (Cameron and LaPoint 1978), and are suspected of altering the amphibian habitat in wetlands impacting populations of various frog species (Adams and Saenz 2012; Cotten et al. 2012; Leonard 2005).

Economic Damage

Chinese tallowtree is one of the most serious weeds in the southeastern United States. As of 2008, this invasive species was estimated to cover nearly 185,000 ha of southern forests (Invasive.org 2013). As the existing range of tallow is expected to increase, the projected timber loss, survey, and control costs also may increase. Cost estimates for controlling tallow infestations in forestlands of eastern Texas, Louisiana, and Mississippi range from $200 million to $400 million in the next 20 yr (Wang et al. 2012a). In Florida, between 1998 and 2007, the Florida Department of Environmental Protection, Bureau of Invasive Plant Management (DEP-BIPM) spent nearly $750,000 treating tallow on more than 2023 ha of natural areas in north and central Florida (G. Jubinsky, Florida Fish and Wildlife Conservation Commission, personal communication).

Risk to Human and Animal Health

Chinese tallowtree historically has been considered a poisonous plant. However, documentation to support this has been scarce (Nelson 2011). According to some accounts, the terminal leaves and un-ripened fruits were responsible for poisoning cattle (Forero et al. 2011; Nelson 2011; Russell et al. 1969). Tallow leaves contain numerous flavonoids and tannins that could be responsible for this poisoning (Wang et al. 2012c). Finally, allergic reactions have been reported in people sensitive to tallow pollen (www.pollenlibrary.com).

Potential Conflicts of Interest

Tallow has been cultivated in China for 14 centuries for the production of oils, waxes, and more recently as a source for biofuel (Boldor et al. 2010; Zheng et al. 2005). This species has abundant whitish sarcotesta in the fruit, which is used for the production of candles and soap (Esser 2002; Jamieson and McKinney 1938). In China, the plant also is used as a source of black dye, as a timber tree, and as an ornamental. Tallow was introduced to the United States in the late 18th century for production of vegetable tallow or *Stillingia* oil. Later, in the 1920s, tallow was repeatedly introduced into the western Gulf states (Jones and McLeod 1989) but these efforts were apparently abandoned for many reasons, among them a pathogen that occurred in the fruit (Jamieson and McKinney 1938). Subsequently, the plant has been marketed commercially for its bright orange leaf color that appears in the autumn (Nelson 2011). Despite its potential value, tallow has a limited number of wildlife and commercial uses. Tallow has been valued as a source of nectar for honeybees (Lieux 1975). Tallow fruits may be eaten during winter by several species of birds (Conway et al. 2002). However, when fed only fruits of this species the birds suffered nutrient deficits and lost body mass (Baldwin et al. 2008).

Current Means of Control

Tallow is considered a prohibited noxious weed in several states in the southeastern United States. These regulations prohibit any living part of the plant to be introduced, possessed, moved, or released. The states that have regulated tallow include Florida, Mississippi, Louisiana, and Texas (USDA-NRCS 2013). Tallow is listed as a Category I invasive by the Florida Exotic Plant Pest Council [FLEPPC] (FLEPPC Plant List Committee 2009). These are species that are altering native plant communities by displacing native species, changing community structures or ecological functions, or hybridizing with natives. Similar advisories are posted by other regional state chapters of the exotic pest plant councils and U.S. Forest Service (Southeast Exotic Plant Pest Council [SEEPC] 2001; Invasive.org 2013).

Currently, the main approaches for controlling tallow in the United States are mechanical, physical and chemical; integrated approaches are often used (McCormick 2005). Integration of these approaches was initially problematic and was not widely adopted (Jubinsky and Anderson 1996), although more recent hack/squirt and basal bark treatments are gaining popularity (McCormick 2005). Mechanical control initially used heavy machinery to remove plants. But this method has proven impractical and counterproductive, as cut tallow trees will resprout, producing multiple small shoots (Scheld and Cowles 1981; Thorpe 1996). Physical control methods, such as manipulation of water levels and prescribed burns, have variable success and cannot be used in all situations (Matlack 2002). Although fire can kill tallow trees, it offers only temporary relief and its effect is highly variable (Grace 1998). In response to this type of disturbance, the plant will vigorously resprout aboveground and produce root sprouts some distance from the original tree. Additionally, tallow may convert a normally pyrogenic site to one that is nonflammable, potentially altering the fire-maintained site, such as a coastal prairie. The end result is the site becomes dominated by tallow following such disturbances (Grace 1998; Smith et al. 1997). Cultural means of control include sheep and goat grazing, although poisoning of cattle has been reported (Russell et al. 1969). Herbicides are costly, only offer a temporary means of control, and may damage nontarget species. Modern methods integrate herbicidal and mechanical control (e.g., hack/squirt) that minimize exposure to nontarget plants. The herbicidal controls include basal bark applications of triclopyr, 2,4-D or picloram applied to foliage (Bruce et al. 1997).

Potential for Biological Control

Biological control of tallow presents a potentially safe and cost-effective option that can be a component of an integrated pest management program. As this species was cultivated for centuries in China, many species of fungal pathogens and insect pests are known (Zheng et al. 2005). The specialists of these species are candidates for biological control of tallow that can be screened for possible release in the United States. Three fungal pathogens and 115 species of arthropods that have been reported to damage tallow and related members of the *Triadica* genus in China. Many of these species are generalist defoliators but a few are specialists and at least two species showed promise following tests conducted in China (Huang et al. 2011; Wang et al. 2012b).

Herbivores in the United States that feed on tallow include mostly generalists, such as the Texas species *Melanoplus angustipennis* Dodge, and *Orphullela pelidna* Burmeister (Orthoptera: Acrididae) (Lankau et al. 2004; Siemann and Rogers 2003). Garden plots grown in Florida are routinely damaged by generalist larvae of *Spodoptera latifascia* Walker (Lepidoptera: Noctuidae), and adults of the invasive weevils *Myllocerus undatus* Marshall, *Pachnaeus litus* (Germar), and *Diaprepes abbreviatus* (L.) (Coleoptera: Curculionidae) (Wheeler, unpubl. data). Tallow plants are visited by predators including *Crematogaster* spp. (Hymenoptera: Formicidae), possibly feeding on extrafloral nectar (Wheeler, unpubl. data). The only specialist feeding on tallow known from the United States is the moth *Caloptilia triadicae* (Lepidoptera: Gracillariidae), whose larvae mine and form blotches on the leaves (Davis et al. 2013). This adventive species has been reported from nearly all the tallow-infested areas of the southeastern United States (Fox et al. 2012). *Caloptilia triadicae* is thought to be of Chinese origin and was first discovered in the United States in 2004 (Fox et al. 2012).

One of the best candidates for tallow biological control is the root feeding beetle *Bikasha collaris* (Baly) (Coleoptera: Chrysomelidae). This species causes both belowground and aboveground damage to the plant by larval and adult feeding, respectively (Huang et al. 2011, 2012). The host specificity of both feeding stages will need to be tested against a range of valued Euphorbiaceae species. Special attention will be paid to the species most closely related to tallow (Table 1). Root-feeding beetles have a history of being effective biological control agents of other weeds. Examples include the flea beetles *Aphthona* spp. used against leafy spurge (*Euphorbia esula* L., Euphorbiaceae) (Hansen et al. 1997) and *Galerucella calmariensis* L. (Coleoptera: Chrysomelidae) on purple loosestrife (*Lythrum salicaria* L., Lythraceae) among other species (Blossey and Hunt-Joshi 2003). Additional biological control agents of tallow that look promising include a defoliator *Gadirtha inexacta* Walker (Lepidoptera: Noctuidae) (Wang et al. 2012b). Like many weeds, a number of agents may be needed to control this invasive species (Center et al. 2012).

The introduction of exotic organisms to achieve classical biological control constitutes a degree of risk to native fauna and flora. However, doing nothing to resolve invasive weed problems accomplishes little and is not neutral (Strong and Pemberton 2001). The risk of biological control agent introductions to valued plants needs to be weighed against the agent's potential effectiveness in reaching conservation goals. If a biological control introduction has negative consequences, the effects may be difficult to reverse as agents are persistent, may spread throughout the weed's range, and are difficult to control following release. To avoid this unintended event, a risk–benefit–cost analysis can be a useful decision-making tool when considering the suitability of a candidate biological control agent release (Lonsdale et al. 2001; Sheppard et al. 2003). This analysis includes several components outlined elsewhere (Lonsdale et al. 2001; Sheppard et al. 2003). One component listed, communication of the risks and benefits of biological control, is critical to the analysis. The lack of transparency when conducting biological control projects has been criticized (Strong and Pemberton 2001) and is a primary reason for conducting this feasibility analysis.

Chinese tallowtree continues to be one of the most troublesome weeds of coastal wetlands and other riparian areas of the southeastern United States. The current management practices (mechanical, physical, cultural, and chemical) require repeated applications extending over several years and appear to be only marginally successful in the long term. By the integration of biological control with the current methods, a coordinated effort will have an improved chance of reducing tallow populations. Several potential biological control candidates appear to be specific to the weed and are being developed for tallow. When practiced safely, biological control has great potential to impact the target weed with minimal risk to valued plants. It also may comprise an important component of an integrated control effort. Such a coordinated and sustained approach should be pursued to bring significant reductions in the levels of the tallow infestation. Based upon the information provided herein, especially regarding phylogenetic isolation of tallow and success documented in similar weed projects (e.g., leafy spurge and *Aphthona* spp.), the prospects are good for biological control to contribute to the management of this invasive weed.

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