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BIOLOGY ECOLOGY AND CONTROL OF TROPICAL SODA APPLE (*Solanum viarum*)

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ABSTRACT

Tropical soda apple (Solanum viarum) is a perennial weed that is a serious problem in many perennial grass pastures of Florida and throughout the southeastern United States. Tropical soda apple (TSA) was recently reported in Australia and could possibly be present in other Asian-Pacific Countries. Field and laboratory research in the U.S., primarily in Florida, on the biology, ecology, and control of TSA has resulted in weed management strategies that will benefit Asian-Pacific Countries that are infested with TSA or at risk for invasion by TSA. TSA is unpalatable to livestock and can infest a pasture or native area in 1-2 years resulting in lower stocking rate. At maturity, TSA is from 1 to 2 m tall; stems and leaves have broad-based white to yellowish prickles; the fruit is globular, about 2 to 3 cm in diameter and yellow when mature. Night temperature generally exerted a greater and more consistent effect than day temperature on plant growth and development. In the US, the potential ecological range for plant growth and development is greatest over latitudinal ranges of 15 to 33 degrees S, which is similar to its native South America. Throughout the year, this plant will have immature and mature fruit present that ensures large numbers of viable seeds (@40,000 per plant) with an average germination rate of 70%. Seedling emergence in Florida primarily occurs from August through March compared with April through October for other southern states. Seed in the soil can remain dormant for two or more years though germination will rapidly occur when conditions are favorable. Tropical soda apple has been observed as a weed in agricultural land and in natural areas. The TSA seed is spread by cattle, wildlife, moving water, and anthropogenic activity (contaminated hay, grass seed, shipping cattle, and sod production). Cattle and wildlife spread TSA by consuming the fruit and spreading the seed via feces. Cattle grazing TSA infested areas should be considered a major seed dispersal vector. Tropical soda apple can tolerate a frost or freeze but the foliage will suffer cold damage with some plant mortality. Control strategies include herbicides, biological (insects, viruses), and cultural practices. Successful (90-100%) control has been reported for the herbicide aminopyralid (Milestone), a beetle known as Gratiana boliviana (TSA beetle), and a virus called Tobacco mild green mosaic tobamovirus. An integrated weed control strategy that includes prevention (early detection, rapid response) and control is the best longterm strategy to managing TSA infested areas in the U.S. or Asian-Pacific Countries.

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BIOLOGY AND ECOLOGY OF THE WEED

TSA Description

At maturity TSA is from 1 to 2 m tall. Stems and leaves have broad-based prickles up to 20 mm long (Mullahey *et al.,* 1993b). The prickles are more evident on the petiole and main veins than on the stems. Leaves are alternate, 10-20 cm long and 6-15 cm wide, and are shallow or sometimes deeply divided into broad pointed lobes. Both surfaces of the leaf blade contain glandular and non-glandular trichomes with the upper surface displaying a velvety sheen. The lower surface has stellate trichomes (Wunderlin *et al.,* 1993). White flowers with cream-colored anthers are borne a few together and hidden beneath the leaves (Coile, 1993). Fruits are globular, glabrous, about 2-3 cm in diameter and yellow when mature. The plant is readily identified by its immature fruit, which is green with white mottling like immature watermelon fruit. Each mature fruit contains about 400 light red-brown seeds that have a diameter of approximately 2.5 mm. Seeds are only moderately flattened and are found in a mucilaginous layer containing a glycoalkaloid called solasodine.

Solanum viarum is a species belonging to the *Solanum Acanthophora* of the prickly subgenus *Leptostemonum* (Nee, 1991). This perennial shrub has been misidentified in the literature as *S. khasianum, S. aculeatissum* (Nee, 1991), and *S. reflexum* (Morton, 1976). Literature on TSA focuses on increasing the solsadine content (Patil and Laloraya, 1981; Pingle and Dnyansagar, 1980), berry yield (Reddy *et al.,* 1991), and reducing number of spines (Reddy and Krishnan, 1988). This plant was cultivated as a source of solasodine, a nitrogenous analogue of diosgenin, and used as a substitute for diosgenin in the synthesis of steroidal drugs. Mexico was the largest producer (750 tons/year) of diosgenin, with India using about 250 tons/year (Sahoo and Dutta, 1984). Apparently, cultivation of TSA for the glycoalkaloid has significantly declined or completely stopped.

TSA Distribution

In its native South America (Brazil, Paraguay, and Argentina), TSA is found over latitudinal ranges of 13 to 33 degrees S, occurring at low elevations in eastern Brazil to Paraguay, Uruguay, and northeastern Argentina (Nee, 1991). Potential ecological range of this weed is dependent upon photoperiod and diurnal temperatures (Patterson *et al.,* 1997). A regression model was calculated to predict the percent maximum growth of TSA during each month from March through November at diverse sites throughout the US. Temperatures at sites in southern US states (latitudinal range 27 to 33 degrees S) support 30% or more of maximum growth from April through October compared to northern states (latitudinal range 33 to 40 degrees S) where that growth rate is supported only from June through

September. Southern states are at greater risk for TSA invasion because of enhanced plant development and reproduction. Further north and west, growth is more seasonally restricted. Extrapolating this information to the southern hemisphere, it would appear that Asian-Pacific Countries in the latitudinal range of 15 to 33 degrees S are at greatest risk for TSA establishment and persistence. Countries south of latitude 33 degrees S are at some risk from TSA invasion but fruit production is more limited and poor seed survival through the winter season reduces the risk of re-establishment. These countries should actively scout for TSA and have an aggressive management plan to remove new plants or patches (early detection, rapid response).

In Florida, TSA is found in southern Florida, though movement north toward the Florida panhandle has been documented. The agricultural land area infested with TSA was estimated at 10,000 ha in 1990, 61,000 ha in 1992, and, according to a TSA Census of beef producers, 164,000 ha in 1993 (Mullahey *et al.,* 1993a). If all land systems (natural and agricultural) were included, the area now infested with TSA in Florida would approach 300,000 ha. This exponential spread of TSA from 1990-93 in Florida should be cause for great concern among people in agriculture and those that manage natural systems. Early detection and rapid response to control plants and preventing or reducing the soil seed buildup by controlling existing plants before the plant produces fruit (i.e. seed) will slow the exponential growth that Florida experienced in the 1990's.

TSA Biology

Though TSA is an indeterminate plant in Florida, flowering and fruit production in Florida is concentrated from September through May (fall and winter seasons) due to favorable photoperiod and day/night temperatures (Mullahey *et al.,* 1993b). Greenhouse grown plants flowered about 60 days after emergence and fruit were produced by about 105 days after emergence (Patterson *et al.,* 1997). In this study, TSA produced flowers across the full range of daylengths evaluated, indicating that no naturally-occurring photoperiods in the continental US are likely to limit the ability of TSA to grow and reproduce. In field studies, flowering of TSA regrowth following mowing begins about 50-60 days after the mowing. Fruit begins to form approximately 70-90 days after mowing (Mullahey *et al.,* 1996). Fruit production (i.e. seed) is similar to flowering, ensuring large numbers of viable seeds (@ 45,000 per plant). Seed germination ranges from 30-100%, though average germination of seed from mature fruit is about 70%. Consequently, during one year, a single plant could supply enough viable seed to produce 28,000-35,000 new TSA plants. Seed will not germinate inside the fruit and seed removed from the fruit need to dry (aging process) before germination occurs. Scarification increases the rate and total germination. Herbivore consumption and subsequent passage of seed in feces is the primary seed dispersal mechanism for this weed in Florida.

Seed viability is related to fruit maturity (color) and fruit diameter; the larger the fruit diameter, the higher the seed viability. However, smaller diameter, yellow fruit (i.e. mature) do contain viable seed. White seed (immature seed) germinate and these are typically present in small diameter, green fruit. Reports suggest fruit size becomes constant after 65-70 days of development (Kaul and Zutshi, 1982).

Plant regeneration can also occur from the roots (Mullahey and Cornell, 1994) so hand weeding of plants is successful if the root system is removed.TSA can store a high concentration (20 to 35%) of total non-structural carbohydrates (TNC) in the roots and stems (Mullahey and Cornell, 1994). TNC concentrations were higher from December to February than during the spring and summer months. Beginning in January, TNC concentrations declined in the root and were probably mobilized for plant growth and development. This also explains the rapid regrowth (i.e. 2 weeks) of TSA following a freeze or mowing event.

Literature reports indicate that seed can remain dormant for months, though the average period of dormancy was 1 month (Pingle and Dnyansagar, 1979). Seed longevity studies in field soil conditions evaluating soil moisture effects on seed viability showed TSA seed remained viable over 260 days in saturated soils (-0.0 bars), while viability in drier soil (< -10 bars) was reduced up to 60% within 260 days (Mullahey, unpublished data). These results confirm field observations that TSA seed can remain viable in the soil for up to one year or longer. Preventing a soil seed-bank of TSA seed (i.e. early detection, rapid response) will greatly increase the chances of successfully removing TSA from a pasture.

Tropical soda apple contains a glycolalkaloid, solasodine, that is found in the mucilaginous layer around the seeds. Solasodine, a nitrogen analogue of diosgenin, is used in the production of steroid hormones. These steroids have been useful in the treatment of cancer, Addison's disease, rheumatic arthritis, and in the production of contraceptives. Maximum content of solasodine in TSA fruit occurred when fruits changed color from green to yellow (Kaul and Zutshi, 1982). Solasodine content in TSA ranges from 4-10%, though the solasodine content decreases with the onset of post fruit maturity. Solasodine is poisonous to humans. At least 10 fruit would have to be eaten before symptoms of poisoning occurred and a lethal dose would require approximately 200 fruit (Frohne and Pfander, 1983). Though the mature fruit has a sweet smell (like a plum or apple) when the berry is opened, the coated seed has a bitter taste when eaten (Mullahey, personal observation). Apparently the bitter taste does not prevent wildlife and cattle from consuming the fruit.

TSA Ecology

TSA has been observed in pastures, sugar cane fields, vegetable fields, citrus groves, natural areas (oak hammocks, cypress heads, swamps), sod fields, ditch banks, lawns, state parks, nature preserves, landfills, and county municipal parks. It is a common weed in South America, India, the West Indies, Honduras, and Mexico. Native to northern Argentina, and southern Brazil, TSA can be expected to occur in other subtropical areas. How TSA was introduced into Florida is not known. Its introduction into North America probably resulted from seed adhering to people's shoes or escape from cultivation (Mullahey *et al.,* 1993b). In Florida, it is an obligate weed mainly associated with human activities. This plant has been identified as a host for nine viruses that cause economic damage to vegetables (McGovern *et al.,* 1994).

Tropical soda apple is spread by cattle, wildlife, contaminated hay, grass seed, moving water, and sod. Mature cattle and weaned calves consume the fruit and the seed pass through the animal where it is deposited onto the pasture in manure. To determine the survivability of TSA seed in the rumen, 40,000 TSA seed were fed to crossbred steers in individual crates designed for the collection of total fecal production (Brown *et al.,* 1996). Greater than 90% of seed had cleared the digestive tract by 48 hours after feeding. Seed recovery continued for up to 18 days after feeding, however seed collected beyond six days after feeding did not germinate. Therefore, cattle should be held in an area that is TSA-free for at least six days before shipment.

Rapid spread of TSA is often associated with some type of soil disturbance. Discing of a field, cattle congregating around a feeder, cleaning of ditch banks, or feral hogs rooting in a field appear to provide a favorable environment for TSA germination, establishment and growth. Standing water will stress the plant, even cause plant loss, but a new plant will emerge from seed once the area begins to dry. Cypress heads will have TSA in the center of the head until the summer rains completely flood the area. Then the TSA will die back to the outer regions (drier areas). As the water in the cypress head recedes during the winter, the TSA will begin to occupy (new plants from seed) the inner regions of the cypress head. Ephemeral wetlands could be susceptible to invasion by TSA during the dry season.

Loss of carrying capacity and shade areas for cattle are two of the main production losses from TSA. A census of Florida cattlemen in

South Florida was conducted to determine the level of infestation (low, medium, or high), based on ground cover, and the hectares associated with each level (Mullahey *et al.,* 1994). Census results indicated a yearly production loss due to decreased carrying capacity and heat stress of $11 million per year. This figure was based on 157,018 ha infested with TSA. If we assume the same levels of infestation, but use current data on infested pasture land (405,000 ha), the economic loss would approach $29 million for Florida ranchers.

Recently, people in Florida observed a "natural decline" in older stands of TSA in pastures. Some of these pastures were heavily infested with TSA for a period of years. Suddenly, the TSA plants disappeared without any management from the rancher. Scientists suspect the decline is associated with soil pathogens and damage from insects and nematodes.This decline is not predictable and it does not occur in all pastures or areas.

Implication of Biology and Ecology for TSA Management Strategies

For invasive weeds, weed biology and ecology information is critically important to developing effective weed management strategies. Unfortunately, for the state of Florida, this information was not available during the period of time (1990-95) when TSA spread exponentially (4,050 ha to 202,500 ha). Early management efforts focused on chemical control with weed biology and ecology studies starting in the mid 1990's. Knowledge about plant growth and development, fruit production, seed development, vectors of spread and habitats at risk for invasion have collectively resulted in the development of economical, effective TSA management strategies. These strategies include prevention, control, and monitoring. It is important that Asian-Pacific countries apply these strategies when TSA is initially detected. Failure to do so could allow TSA to exponentially spread as it has in Florida and thus miss the opportunity to eliminate the weed.

Prevention

Understanding that TSA spreads primarily from seed, ranchers need to prevent the movement of contaminated products onto the ranch. Preventing the spread of TSA seed limits the movement of this noxious weed and is a form of weed control. The seed is coated in a mucilaginous substance that enables it to "stick" to whatever it touches. Seed is transported in sod, hay, grass seed, and cattle. Seed will adhere to vehicles such as trucks, tractors, or mowing equipment. Ranchers should clean equipment to remove the seed before moving it from an infested pasture to another pasture or location. Hold cattle in a pasture for six days to allow time for seed to pass through the digestive tract. Confining the weed to small areas makes it easier to control. If hay or grass seed is purchased that is contaminated with TSA, refuse to buy any more hay or seed from that supplier. Monitor the areas where hay is fed to cattle for new TSA plants so these plants can be removed before they produce fruit.

Control

Control strategies for TSA include herbicides and biological control. Initial herbicide studies focused on preherbicide mowing followed by application of post-emergence herbicides such as Remedy® (1.12 kg/ha triclopyr) applied (374 L/ha) to bahiagrass pastures (Mullahey *et al.,* 1993 a & b; Akanda *et al.,* 1997; Mislevy *et al.,* 1999). Remedy provided excellent control (90-100%) of juvenile TSA but the herbicide had two limitations: inconsistent control if plants are fruiting and no soil residual activity to control new, emerging TSA seedlings in the treated area. Additionally, the mowing and the herbicide program cost about USD $21/ha which was too expensive for most ranchers. Recent studies have shown excellent control with Milestone and this herbicide possesses superior post-emergence and/or preemergence control relative to Remedy (Ferrell *et al.* 2006). Additionally, no preherbicide mowing is required when using Milestone thus reducing the total treatment cost. Milestone® (0.08 kg/ha aminopyralid) applied (187 L/ha) in the winter months in Florida provided excellent control of TSA and this treatment increased the duration of grazing at a time of the year when nutritional requirements are higher because cows are lactating. Consistent, excellent control (95%) was observed with Milestone applied at broadcast rates ≥ 0.08 kg/ha (Ferrell *et al.* 2006) or as a spot treatment at 15-20 ml/9.46 l (Sellers *et al.,* 2009). Milestone is commercially available in prepackaged mixes with other herbicides which will provide more broad spectrum weed control in pastures.

Biological control using insects collected from Brazil has been effective in controlling TSA. Preliminary surveys in Brazil and Argentina to collect insects for evaluation resulted in the collection of the leaf-feeding beetle *Gratiana boliviana* (Coleoptera: Chrysomelidae). This beetle was the first biocontrol agent introduced against TSA and it was released in Florida in the summer 2003 (Medal and Cuda 2003). The beetle quickly established at release sites in southern Florida and feeding damaged the foliage and significantly reduced fruit production. Beetles showed a dispersal ability from the release sites of 1.6 km per year. Two years after the beetle release, many of the TSA plants at one release site were replaced by desirable pasture grasses. To date, no negative, non-target effects have been observed. Studies continue looking for beetles with more cold tolerance, preference for shade, and insects that feed on TSA flowers such as the adult flower-bud weevil (*Anthonomus tenebrosus*).

A natural, biological herbicide to control TSA is currently under development and is not available for public use at this time. The product is called SolviNix LC and contains a naturally occurring virus called Tobacco mild green mosaic tobamovirus (Charudattan, 2007). Based on extensive field-testing, it has been determined that nearly 100% control of TSA is possible with very small quantities of the virus (8.1 mg to 0.81 g of active ingredient per ha). The virus is best suited for spot-application with a high-pressure sprayer (5.5 to 13.8 bars) depending on the nozzle-to-target distance.

Education and Extension of Information

Information on preventing the spread of TSA and the adoption of integrated management strategies to control TSA evolved through education programs targeting land managers and policy makers in Florida and the southeastern US. The University of Florida, Institute of Food and Agricultural Sciences (IFAS), was the lead organization in creating and disseminating science based information on TSA. However, education was a team effort that included state government officials, federal officials, agribusiness, cattlemen, public land managers, and the media. Information was disseminated using posters, brochures, information cards, PowerPoint presentations, radio spots, DVD's, websites, and trade journal articles. Information was presented during field days, producer meetings, workshops, and seminars. One significant development to educate the ranchers in Florida was the establishment of the TSA Task Force in 1993 by the Florida Commissioner of Agriculture. The task force addressed various aspects about TSA (regulatory, research, education), and its members represented the affected industries along with university officials. Officials from other state agencies throughout the southeastern US joined the task force in an effort to prevent the spread of TSA into other states. The task force was responsible for placing TSA on the Florida Noxious Weed List (1994) and the Federal Weed List (1995). The task force successfully obtained research funding for TSA projects and one project (TSA seed survivability) led to the policy of holding cattle for six days prior to shipping to avoid the spread of germinable seed. This kind of interdisciplinary approach may be most beneficial to Asian-Pacific countries that are infested with TSA.

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