Seasonal Occurrence and Reproductive Suitability of Weed Hosts for Sweetpotato Whitefly, *Bemisia tabaci* (Hemiptera: Aleyrodidae), in South Georgia[1]

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Abstract South Georgia represents an area of intensive agricultural production where cultivated crops serve as hosts of the sweetpotato whitefly, *Bemisia tabaci* Gennadius (Hemiptera: Aleyrodidae), throughout the year. In addition to cultivated hosts, there are numerous weed species present in the agricultural landscape that are undoubtedly responsible for supporting *B. tabaci* population development. This study provided information on the most abundant weed hosts of *B. tabaci* from this region. We evaluated 31 different weed species, of which 16 weed species are reproductive hosts with varying degrees of preference. Suitable weed hosts included cypressvine morningglory (*Ipomoea quamoclit* L.), nodding spurge (*Euphorbia nutans* Lag.), prickly sida (*Sida spinosa* L.), sharppod morningglory (*Ipomoea cordatotriloba* Dennst.), smallflower morningglory (*Jacquemontia tamnifolia* L.), tall vervain (*Verbena bonariensis* L.), and wild poinsettia (*Euphorbia heterophylla* L.). These species are highly abundant and therefore likely influence *B. tabaci* populations in the landscape. Other species including bristly starbur (*Acanthospermum hispidum* DC) and redweed (*Melochia corchorifolia* L.) were highly preferred by *B. tabaci* but not nearly as abundant in the landscape. Furthermore, we identified 10 very common weed species that were poor reproductive hosts including wild radish (*Raphanus raphanistrum* L.), Palmer amaranth (*Amaranthus palmeri* S. Watson), common ragweed (*Ambrosia artemisiifolia* L.), Florida pusley (*Richardia scabra* L.), and henbit (*Lamium amplexicaule* L.).

Key Words reproductive host, pest management, population suppression, leaf area

Sweetpotato whitefly, *Bemisia tabaci* Gennadius, is an economic pest of many crops around the world (Brown et al. 1995, Byrne and Bellow 1991, Naranjo and Ellsworth 2001, Simmons et al. 2008). This insect was introduced into the United States in the late 1980s and has resulted in severe economic losses in vegetable and upland cotton (*Gossypium hirsutum* L.) production systems from California, Arizona, Texas, Florida, Georgia, and South Carolina (Perring 2001). Crop losses can result from direct feeding by adults and immature whiteflies or transmission of more than 100 plant viruses including tomato yellow leaf curl, cucurbit leaf crumple, and squash yellow vein mosaic (Jones 2003). There are multiple *B. tabaci* biotypes,

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and each have differential behavioral and physiological responses to their host plants and insecticides (Horowitz et al. 2005, Hu et al. 2020, Watanabe et al. 2019).

In Georgia, *B. tabaci* is a recurrent pest of cotton and several important vegetable crops grown in the southern part of the state. Current data suggest that the *B. tabaci* populations associated with field crops in Georgia are B-biotype, because there have not been any field reports of Q-biotype (McKenzie et al. 2020). Severity of *B. tabaci* infestation and incidence of plant virus transmission by this vector in Georgia has increased in recent years, possibly due to mild winters that do not terminate hosts. In 2017, an outbreak of *B. tabaci* in Georgia resulted in losses at an estimated economic value exceeding $150 M in cotton and snap bean (*Phaseolus vulgaris*) alone (Cook 2017, Little 2019). Year-round production of vegetable crops, abundant cotton cultivation, and the presence of abundant weed hosts are hypothesized to contribute to maintaining whiteflies in the southern part of Georgia (Sparks et al. 2018).

Weeds are frequently abundant in agricultural production systems, and they have significant influence on crop management practices. Weeds directly compete with cash crops for resources and negatively impact crop production in terms of quality and quantity (Zimdahl 2004). Some weed species also support the development of insect pests and natural enemies, as well as serving as an inoculum source for plant pathogens (Capinera 2005, Norris and Kogan 2000, Oliveria and Fontes 2008). Understanding the relationships between insects (both pests and natural enemies) and weeds provide enormous opportunities to develop nonchemical pest management solutions in crop production (Capinera 2005, Hiljea et al. 2001). This relationship is particularly critical for insect pests that transmit diseases between weeds and agricultural crops (Barreto et al. 2013, McGovern et al. 1994, Srinivasan et al. 2014). For example, tobacco thrips (*Frankliniella fusca* [Hinds]) feeds on common chickweed (*Stellaria media* L.) where it has been shown to acquire tomato spotted wilt virus and subsequently transmit the disease to peanut (*Arachis hypogaea* L.) (Groves et al. 2001, Srinivasan et al. 2014). Insect vectors including thrips and whiteflies have a wide range of reproductive hosts including crop and noncrop or weed species. Among the weed hosts, species that are both reservoir of the virus and reproductive host of the insect vector are critically important for understanding the epidemiology of the virus transmission and developing management strategies.

A highly polyphagous insect pest, *B. tabaci* has a host range of more than 600 plant species from diverse plant families (Bellows et al. 1994, Evans 2007, Mound and Hasley 1978). Among these host plant species, many of them are cultivated crops including cotton, soybean (*Glycine max* L), tomato (*Solanum lycopersicum* L.), snap bean, egg plant (*Solanum melongena* L.), and squash (*Cucurbita pepo* L.) that are nearly cosmopolitan. However, significant differences in diversity and abundance of weed hosts exist across the distribution range of *B. tabaci* around the world (Abd-Rabou and Simmons 2010, Naveed et al. 2007, Simmons et al. 2008, Smith et al. 2014). These differences are prominent among the various regions within the United States that are plagued by *B. tabaci*. Previous studies documented that there are weed hosts of *B. tabaci* unique to each growing region in terms of their occurrence and abundance. Watson et al. (1992) identified six off-season weed hosts as potential sources of whitefly in the Yuma Valley of Arizona. Alkali mallow (*Sida hederacea* [Douglas ex Hook]), London rocket (*Sisymbruium iro*

L.), and spiny sowthistle (*Sonchus asper* [L.]) were the primary winter weed hosts, and whitefly populations could exceed those found on vegetables grown during that time of the year. Riley and Ciomperlik (1997) ranked both weeds and host crops in terms of whitefly-nymph-numerical categories per standardized sample in a survey in southern Texas, which suggested that cucurbit crops, cucurbit weed hosts, *Brassica* crops, and *Solanacea* crops support high whitefly numbers. In contrast to the desert environment of Arizona, dominant weed hosts of *B. tabaci* reported from Florida included redroot pigweed (*Amaranthus retroflexus* L.), Spanish needle, (*Bidens alba* [L.]), tasselflower (*Emilia fosbergii* Nicolson), and wild radish (*Raphanus raphanistrum* L.) (Smith et al. 2015, Stansly et al. 1997). Therefore, it is important to document the weed hosts of *B. tabaci* in a given landscape considering the diversity and uniqueness in regional abundance of plant species.

To be considered a reproductive host, individuals of herbivore insects must be able to establish, feed, and complete their life cycle on the plant. Range of host plant species of *B. tabaci* has been reported based on various field observations, greenhouse studies, and no-choice laboratory experiments (Carabalí et al. 2010, Simmons et al. 2008, Smith et al. 2015). However, observations based on the natural infestations of insects on plant species provide a better understanding of the insect–host relationships in time and space as the composition and seasonality of abundant host plants of *B. tabaci* are difficult to mimic in controlled experimental setting. Objectives of this study were to document the seasonality and potential contribution of key weed hosts that facilitated *B. tabaci* populations in southern Georgia.

Materials and Methods

The authors conducted an extensive area-wide monitoring of *B. tabaci* during 2018 and 2019 in Georgia (Barman et al. 2019, 2020). The monitoring program included placement of 125 yellow sticky cards approximately 8.0 km apart across 23 counties in the southern half of Georgia. Sticky cards were replaced weekly from January 2018 through December 2019. The authors noted that certain weed species were frequently abundant in areas with increased *B. tabaci* captures. In 2018, the authors recorded weed species and their general abundance in and around fields adjacent to the sticky traps. Starting in January 2019, the authors systematically noted presence or absence of each weed species by month and then examined leaves from each of these weed species to ascertain immature *B. tabaci*. Based on the overall abundance of each weed species in and around the field margins observed over the year, a weed species was categorized into high, medium, and low abundance. A weed species with high abundance is the one that was present in near 100% of the fields and could be found over wide areas within those fields. A medium abundance species was observed in approximately 50% of the fields, and its distribution was only found in relatively small areas across the field. A low abundance weed species was observed only in specific habitats, for example, low lying, waterlogged areas of a field.

Presence of both adults and immature stages on the leaf samples was required to confirm that the weed species is a reproductive host of *B. tabaci*. Of the 31 weeds of interest, only 16 harbored immature *B. tabaci*. Leaf samples of 15 of those 16 weed species were collected in 2019 from January through December. We did not include the information on common mallow (*Malva neglecta* Wallr.), which was found to be a good host of whitefly, but this species was not seen except in one vegetable field during the time of this study. In brief, 10–14 fully expanded leaves, preferably collected from middle part (not at the growing point nor the basal most leaves) of several plants of the same species, constituted a sample. Leaf samples were collected from a minimum of three different fields. Each leaf was carefully examined under a dissecting microscope at 20× magnification, and the total number of nymphs was enumerated. Because there were profound differences in leaf size, the total leaf area of each sample was subsequently estimated using a LI-3100 leaf area meter (LiCor, Lincoln, NE). Based on the leaf area in each sample, the density of *B. tabaci* nymphs was converted to a standard 100 cm^2 of leaf area; this method was used to estimate the relative density of immature whiteflies in previous studies (Attique et al. 2003, Naveed et al. 2007, Zang et al. 2020). Furthermore, the number of nymphs per 100 cm^2 was compared with leaf area using correlation. Experimental design was completely randomized, and the responses were analyzed by analysis of variance (ANOVA) with means separation using Tukey's honestly significant difference (hsd) at $\alpha = 0.05$ to detect differences among weed species.

Results

Immature *B. tabaci* were only evident on 16 of the 31 plant species. Considering only the weeds with immatures, leaf area varied widely by plant species. Among the 15 species examined for *B. tabaci* immature density, common cocklebur had the largest leaf area (79.7 ± 4.9 cm^2), followed by tall morningglory (34.0 ± 2.3 cm^2), wild radish (29.7 ± 0.5 cm^2), and smallflower morningglory (27.6 ± 2.3 cm^2). The leaf area was measured lowest in case of cypressvine morningglory (1.3 ± 0.1 cm^2), followed by nodding spurge (2.1 ± 0.2 cm^2) leaves (Fig. 1). Because there was significant variation in leaf area for individual leaves of each plant species ($F = 160.9$; df = 14, 30; $P < 0.005$), density of *B. tabaci* immatures on leaves needed to be standardized to allow for comparisons. Therefore, the *B. tabaci* immature density on leaves was converted to number of immatures per 100 cm^2 leaf area from the actual number of immatures recorded on each leaf sample.

Density of immature *B. tabaci* recorded varied significantly among the different weed species ($F = 31.5$, df = 14, 30; $P < 0.005$; Fig. 2). Among the 15 weed species evaluated, highest density (per 100 cm^2 of leaf) of immature *B. tabaci* was recorded in nodding spurge (550.3 ± 90.1), followed by bristly starbur (427.5 ± 43.3) and redweed (423.0 ± 60.3). Density of *B. tabaci* immatures was similar between tall vervain (249.9 ± 14.4) and cypressvine morningglory (182.8 ± 25.5), both of which were greater than common cocklebur (13.9 ± 2.9), Florida pusley (0.6 ± 0.3), henbit (5.8 ± 1.1), Palmer amaranth (1.1 ± 0.4), tall morningglory (4.6 ± 0.8), and wild radish (2.9 ± 1.4). No correlation was detected between counts of nymphs per 100 cm^2 and the unit leaf area by plant species ($r = -0.37$; df = 15; $P = 0.176$).

A listing of the original 31 weed species, their occurrence by month, abundance in the fields, and relative host suitability to *B. tabaci* is presented in Table 1. There were admittedly many more weed species present in the study area, but, based on

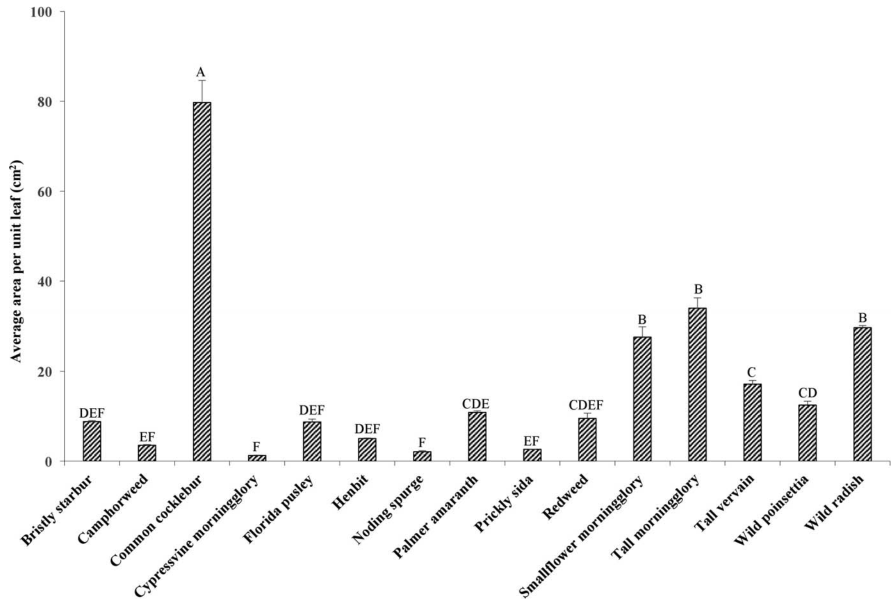

Fig. 1. Mean ± SE leaf area for 15 weed species evaluated for *B. tabaci* host suitability in South Georgia. Means significantly different are followed by different letters, Tukey HSD test, $\alpha = 0.5$.

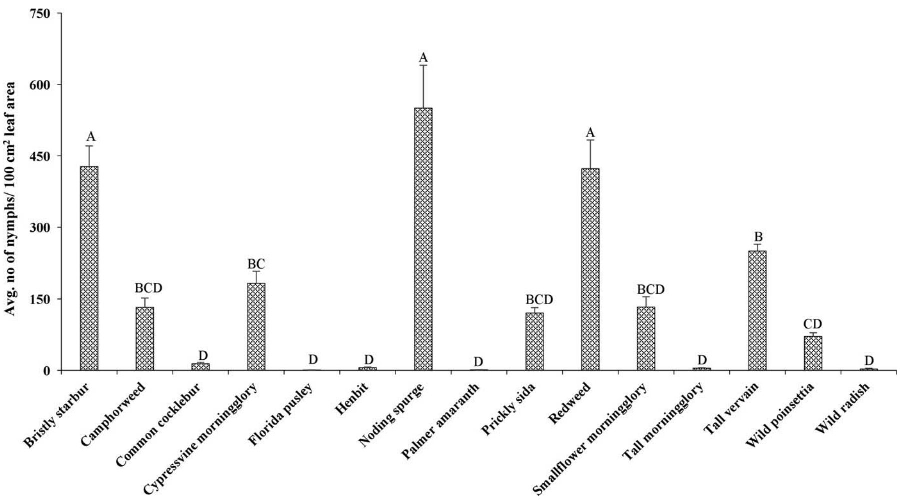

Fig. 2. Mean ± SE density of immature *B. tabaci* observed during 2019 from 15 weed species commonly found in South Georgia. Means significantly different are followed by different letters, Tukey HSD test, $\alpha = 0.5$.

Table 1. List of weed species examined for presence of *B. tabaci* and their suitability as reproductive host in South Georgia.

Sl. No.	Common name	Scientific name	Family	Time of natural presence												Abundance	Host suitability
				J	F	M	A	M	J	J	A	S	O	N	D		
1	Benghal dayflower	*Commelina benghalensis*	Commelinaceae							■	■	■	■			High	-
2	Bristly starbur	*Acanthospermum hispidum*	Asteraceae							■	■	■	■			Medium	+++
3	Camphorweed	*Heterotheca subaxillaris*	Asteraceae								■	■	■	■		Medium	++
4	Common cocklebur	*Xanthium strumarium*	Asteraceae						■	■	■	■	■			Low	++
5	Common mallow	*Malva neglecta*	Malvaceae	■	■	■										Low	+++
6	Common ragweed	*Ambrosia artemisiifolia*	Asteraceae							■	■	■	■			High	-
7	Cutleaf evening-primrose	*Oenothera laciniata*	Onagraceae		■	■	■									High	-
8	Cypressvine morningglory	*Ipomoea quamoclit*	Convolvulaceae							■	■	■	■			High	+
9	Eclipta	*Eclipta alba*	Asteraceae						■	■	■	■				Medium	+
10	Florida pusley	*Richardia scabra*	Rubiaceae							■	■	■	■			High	-
11	Hairy vetch	*Vicia villosa*	Fabaceae		■	■	■									High	-
12	Henbit	*Lamium amplexicaule*	Lamiaceae	■	■	■									■	High	-
13	Jimsonweed	*Datura stramonium*	Solanaceae						■	■	■	■				Low	-
14	Lantana	*Lantana camara*	Verbenaceae	■	■	■	■	■	■	■	■	■	■	■	■	Low	+
15	Nodding spurge	*Euphorbia nutans*	Euphorbiaceae						■	■	■	■	■			High	++
16	Pennsylvania smartweed	*Persicaria pensylvanica*	Polygonaceae						■	■	■	■				High	-
17	Palmer amaranth	*Amaranthus palmeri*	Amaranthaceae				■	■	■	■	■	■	■			High	-
18	Prickly lettuce	*Lactuca serriola*	Asteraceae	■	■	■										Medium	-
19	Prickly sida	*Sida spinosa*	Malvaceae							■	■	■	■	■		High	+
20	Redweed	*Melochia corchorifolia*	Sterculiaceae							■	■	■	■			Medium	+++
21	Sharppod morningglory,	*Ipomoea cordatotriloba*	Convolvulaceae						■	■	■	■				High	+
22	Showy evening-primrose	*Oenothera speciosa*	Onagraceae		■	■	■									Medium	-
23	Smallflower morningglory	*Jacquemontia tamnifolia*	Convolvulaceae						■	■	■	■				High	+++
24	Southern dewberry	*Rubus trivialis*	Rosaceae	■	■	■	■	■	■	■	■	■	■	■	■	High	-
25	Mild smartweed	*Persicaria hydropiperoides*	Polygonaceae						■	■	■	■				Low	-
26	Tall morningglory	*Ipomoea purpurea*	Convolvulaceae						■	■	■	■				Medium	+
27	Tall vervain	*Verbena bonariensis*	Verbenaceae	■	■	■	■	■	■	■	■	■	■	■	■	High	++
28	Tropic croton	*Croton glandulosus*	Euphorbiaceae							■	■	■	■			Medium	+
29	Virginia pepperweed	*Lepidium virginicum*	Brassicaceae		■	■	■									Medium	-
30	Wild poinsettia	*Euphorbia heterophylla*	Euphorbiaceae							■	■	■	■			High	++
31	Wild radish	*Raphanus raphanistrum*	Brassicaceae	■	■	■	■	■							■	High	-

the objective and resources, this list provides information about the most important weed species that contributed to *B. tabaci* reproduction measured by presence of adults and immatures under field conditions. The 31 weed species presented in the list belong to 17 plant families. Among those weed species, 17 species appear to be highly abundant, 9 species of medium abundance, and 5 species are of low abundance in South Georgia crop fields. In terms of host suitability, four species (bristly starbur, common mallow, redweed and smallflower morningglory) ranked high, five were medium, and six were low. There were 14 weed species that were not reproductive hosts for *B. tabaci* infestation in the field. Among the 31 weed species examined, 65% were summer-early fall weeds, whereas 25% were spring weeds. There were three weeds species (lantana [*Lantana camara* L.], southern dewberry [*Rubus flagellaris* Willd.], and tall vervain) that are perennial, suggesting that vegetation could be available for *B. tabaci* infestation throughout the year. Among these three perennial weed species, southern dewberry and tall vervain are highly abundant in South Georgia crop fields, especially on field edges and undisturbed areas within the field.

To visualize the seasonal abundance of preferred hosts of *B. tabaci* observed across southern part of Georgia, we incorporated crop data (Sparks et al. 2018) with estimates from this study to create a graphic that summarized the timing of reproductive hosts (Fig. 3). It is obvious that there are fewer crops and weed hosts during the winter and early-spring (December to April). The primary crops available in the field during this period are kale (*Brassica oleracea* L.), cabbage (*Brassica oleracea* L.), and related cole crops. We found that only one weed species (tall vervain) was important in terms of supporting whitefly populations during the same

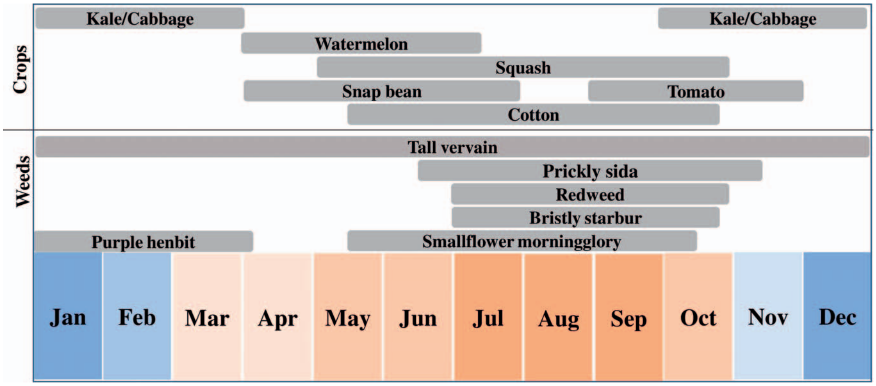

Fig. 3. Seasonal succession of *B. tabaci* hosts including weeds and crops in the South Georgia agricultural landscape.

time period. Considering these data, it appears that there is opportunity to spatially target whitefly both on cole crops and the very limited weed hosts to reduce subsequent insect pressure during summer and fall season. Our study also confirmed that several weed species that are highly prevalent during this critical period (December to April), such as wild radish and cutleaf evening-primrose (*Oenothera laciniata* Hill), that do not contribute toward supporting and increasing whitefly populations.

Discussion

Host suitability of herbivore insects can be determined in various ways as indicated in the literature (Barman et al. 2010, Knolhoff and Heckel 2013, Mostafa et al. 2011). Controlled greenhouse and laboratory study under confined conditions allow researchers to unveil various aspects of insect–plant relationships; however, infestations in the field provide the best opportunity to document actual host preference and successful colonization (Abd-Rabou and Simmons 2010, Riley and Ciomperlik 1997, Stansly et al. 1997). This study provided field-based, realistic, and valuable information about the weed species, which are either highly important or not so important for multiplication of *B. tabaci* populations in South Georgia. Documenting the weed species that do not support *B. tabaci* is equally important as many of the nonhost weed species support beneficial insect populations and pollinators (Gabriel and Tscharntke 2007, Kleiman et al. 2020). Therefore, field studies similar to this are critical in providing information on target weed species of pests and sources of disease inoculum for sustainable management of pests and diseases (Gitaitis et al. 2002). For example, wild radish is one the most abundant weeds during winter and early spring across South Georgia and supports beneficial insects and pollinators; however, this species was clearly not a suitable host of *B. tabaci*. Similarly, Palmer amaranth is a nearly cosmopolitan weed across this region that is available throughout the year when temperatures are above freezing. We found that under field conditions, Palmer amaranth is not a preferred host of *B.*

tabaci and did not support insect multiplication as evident by very few immatures even under heavy insect pressure. This observation agrees with previous finding that redroot pigweed was a poor host of *B. tabaci* in the United States (Smith et al. 2014, Muñiz 2000).

Sustainable management of *B. tabaci* in South Georgia requires understanding of the relationships between the insect and host plants, which includes both cultivated and weed species in the region. Row crop and vegetable producers apply insecticides when *B. tabaci* populations exceed established treatment thresholds in crops such as cotton, squash, and tomatoes. However, cultural control options such as management of weeds and timely destruction of cop residues can play a vital role in reducing *B. tabaci* populations (Sparks et al. 2018). Among the 31 weed species studied, bristly starbur, cypressvine morningglory, nodding spurge, redweed, and smallflower morningglory were highly preferred weed hosts of *B. tabaci* during summer and early fall in the study area. These five annual weed species attract and support reproduction of *B. tabaci* and thus contribute to increased populations of *B. tabaci*.

The authors propose that winter weeds or perennial weeds likely play a critical role in persistent occurrence of *B. tabaci* populations in South Georgia. Because *B. tabaci* reproduces year-round and requires living foliage for survival, only weed species with green leaves during winter months are likely to be candidate plants for sheltering *B. tabaci* populations (Gerling 1984). Identifying and managing such weed species could be vital to disrupting the life cycle of *B. tabaci,* and further reducing the abundance of those weeds during the winter could severely limit *B. tabaci* populations at this critical time. Among the 31 weed species examined in this study, only 3 were perennials that could potentially serve as overwintering hosts due to their year-round availability of green leaves. We found that lantana is a suitable host of *B. tabaci* as reported previously (Attique et al. 2003, Li et al. 2011, Romba et al. 2018) but was rarely present in field margins in South Georgia. Conversely, southern dewberry and tall vervain are two of the most abundant plants in field margins across the entire South Georgia region. Multiple observations in the field and examination of leave samples from different locations indicated that tall vervain can support overwintering *B. tabaci* populations. Southern dewberry, a perennial species highly abundant in this region, appears to be a nonhost for *B. tabaci* in field conditions, and our no-choice feeding experiment confirmed this observation (A. Barman, unpubl. data). Henbit and wild radish were widely distributed and common in the study area but were not suitable *B. tabaci* reproductive hosts. A winter weed, common mallow, was an excellent host of *B. tabaci*, but it is not widely present in the study area (Table 1). It appears that several mallow species such as alkali mallow and little mallow (*Malva parviflora* L.) are preferred hosts of *B. tabaci* in Arizona cropping systems (Watson et al. 1992).

Because *B. tabaci* is a vector of many viruses that cause devastating plant diseases, additional studies are needed to explore whether the suitable weed species identified in this study are also reservoirs of any virus(s). A recent study showed that a common pigweed could be a reservoir in transmission of tomato yellow leaf curl virus (TYLCV); Legarrea et al. (2020) showed that *B. tabaci* individuals were able to both inoculate and transmit the virus from Palmer amaranth to healthy tomato plants. However, field observations based on our study and work from other research groups have confirmed that Palmer amaranth, a highly abundant and difficult to control weed, is not a preferred host of *B. tabaci*, which reduces the risk of TYLCV transmission. Furthermore, Smith et al. (2015) evaluated four weed species as hosts of TYLCV and found that Spanish needle, tasselflower, and wild radish do not serve as reservoirs for the virus.

Bemisia tabaci populations subsisted at low population density during the winter and early spring months in the study area. Once gaining a foothold in the spring, those populations continued to increase through the summer months when temperature is favorable and abundant foliage is available. To design a preventative management strategy for *B. tabaci*, it is important to know the seasonal succession of both crop and weed hosts of the pest. Although summer weeds are important for enhanced multiplication of *B. tabaci* populations, winter weeds are likely to be most critical for supporting continuity of the pest life cycle in the absence of large acreage cultivated crops like cotton. Considering the seasonal succession of major crop and weed hosts of *B. tabaci* in the region (Fig. 3), the data suggest that noncrop vegetation management efforts during winter and early spring should be focused on weed species such as tall vervain and common mallow to minimize populations that will later increase on spring vegetables and summer row crops. Similarly, growers should attempt to limit *B. tabaci* populations that subsist on cultivated crops (i.e., kale and cabbage) that are grown during the winter months.

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